OLUME 107 PART A NUMBER 31 FEBRUARY 1960

The Proceedings

OF

THE INSTITUTION OF ELECTRICAL ENGINEERS

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PART A

POWER ENGINEERING

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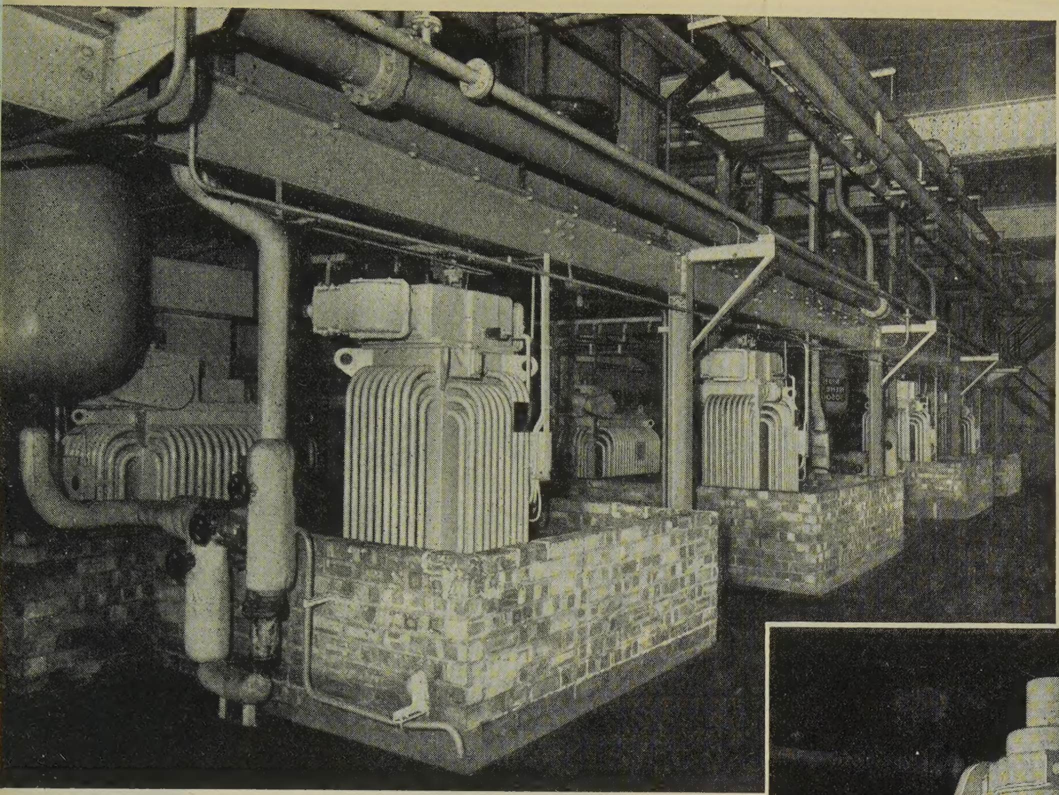

Battery of eight 100 kVA oil-cooled induction regulators for heater control. (Imperial Chemical Industries Ltd.)

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The induction regulator has a number of advantages for the provision of a continuously-variable voltage. It has a high efficiency and low reactance, does not cause harmonic distortion or low power factor, operates without sliding contacts and is readily adaptable to various forms of automatic control.

L.S.E. have had considerable experience in the manufacture of induction regulators and can offer equipments for capacities up to about 5,000 kVA, either low or high tension.

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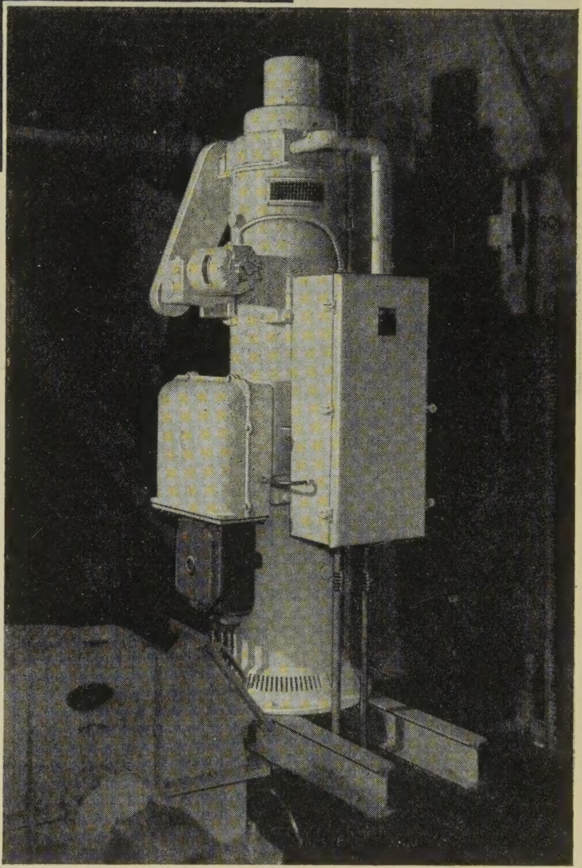

One of six 35 kVA forced-air-cooled single induction regulators, with integral transformer and fan, controlling hot traps at the Dounreay Fast Reactor. (United Kingdom Atomic Energy Authority.)

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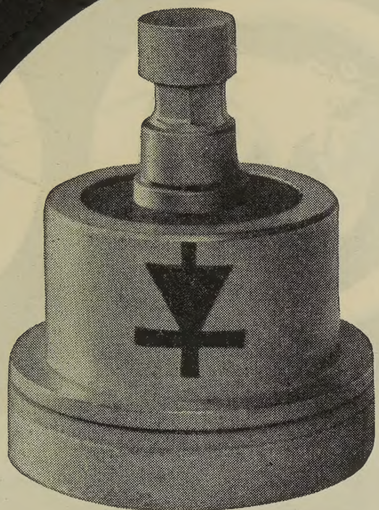
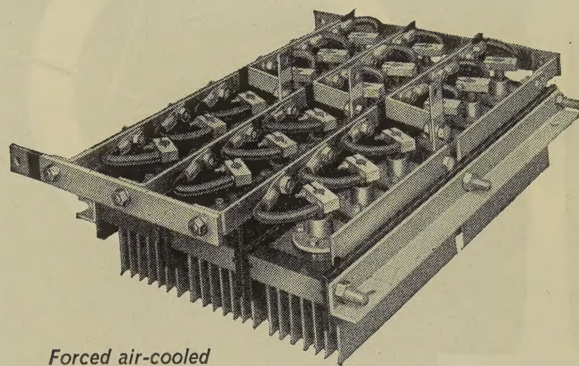
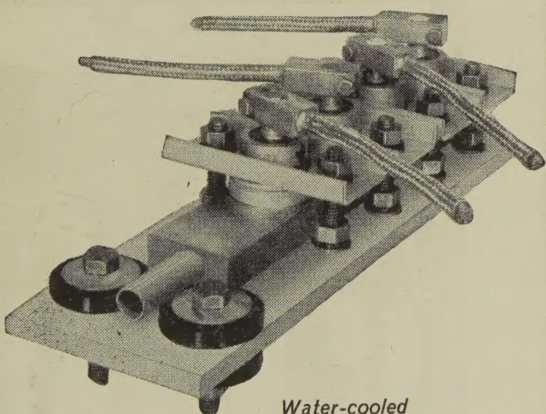
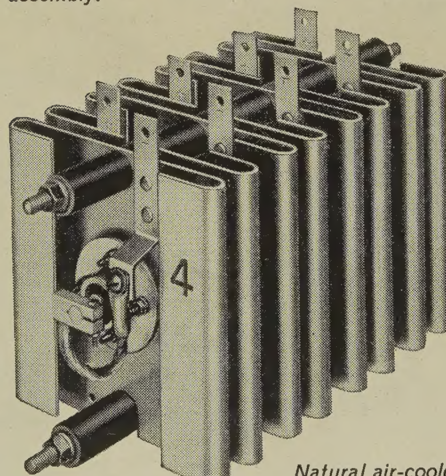




Forced air-cooled assembly.



Water-cooled assembly.



Natural air-cooled assembly.

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HEAVY CURRENT	Up to 120 amperes.
EFFICIENT	Up to 99 per cent.
RELIABLE	Advanced hard solder techniques used in manufacture ensure long life.
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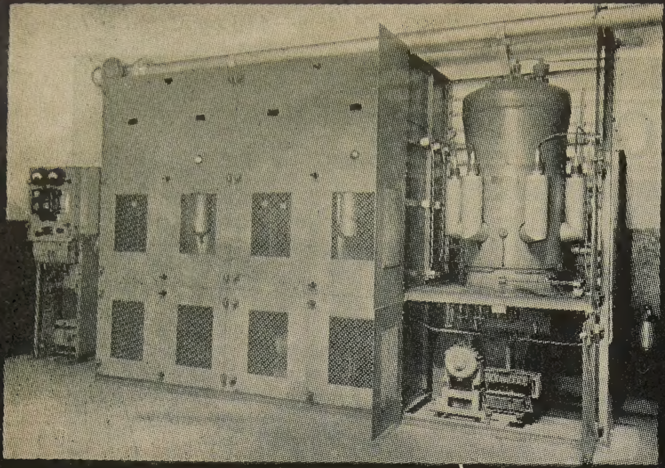

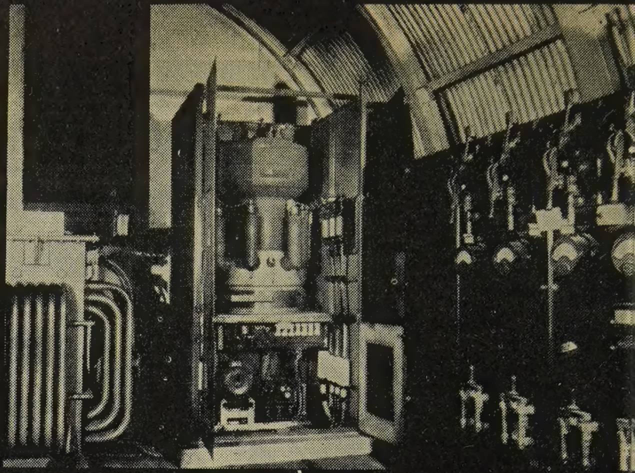

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300 kW at
530 V rectifier in
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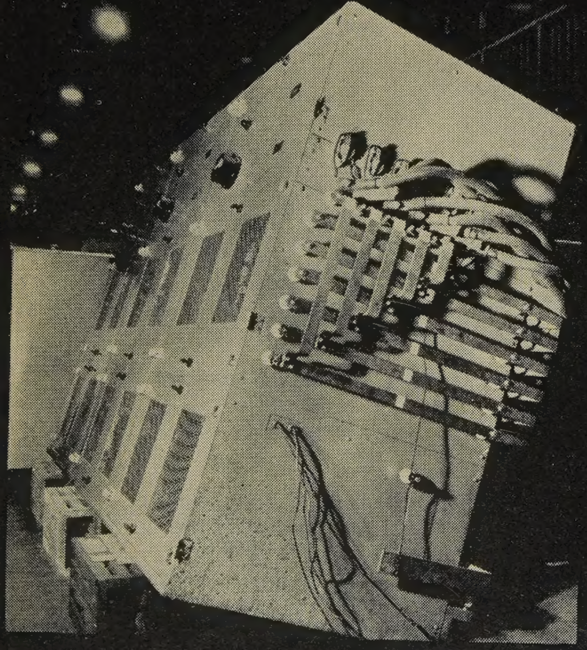
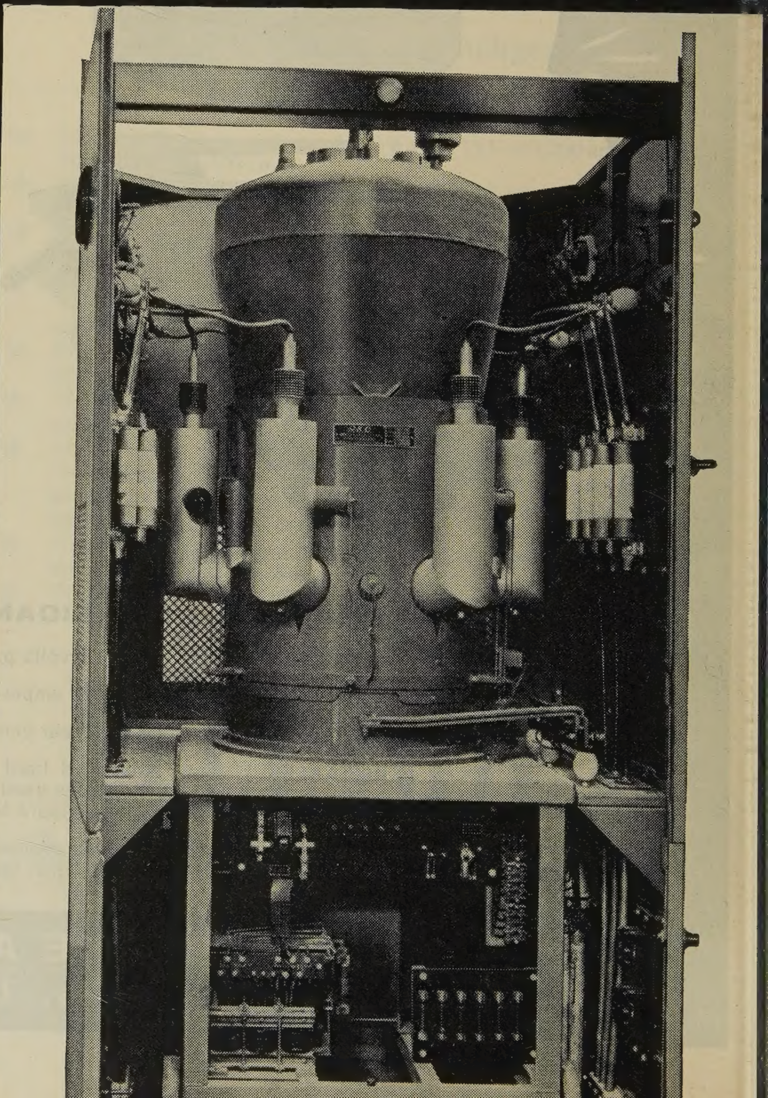
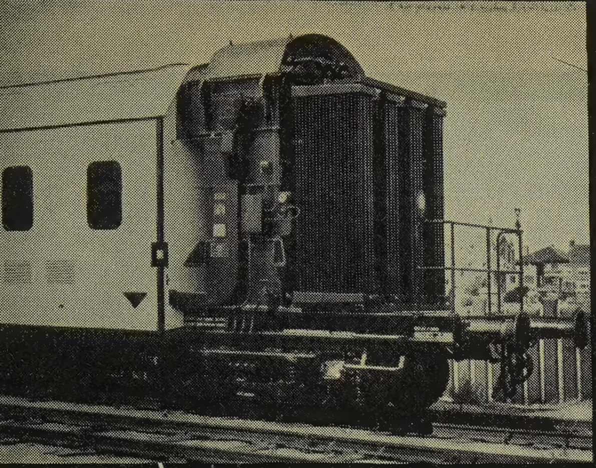
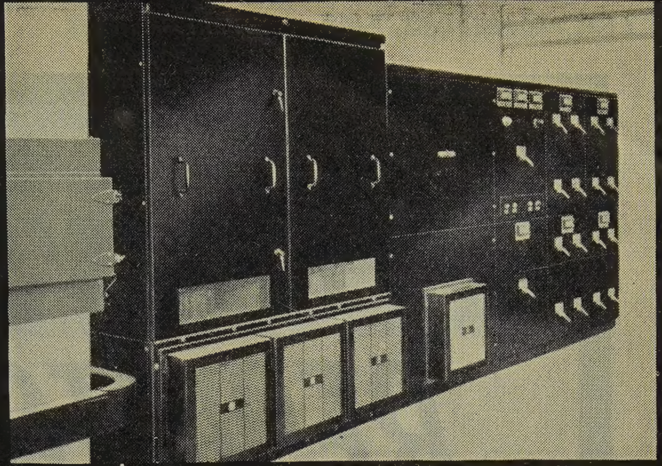
(300 ft. below)
in Australasia.



A 400 kW, 225V, G.E.C. grid-controlled pumpless air-cooled steel tank rectifier equipment undergoing "inclining test". This equipment formed part of a comprehensive contract for a large floating dock for the Admiralty, for which the G.E.C. acted as main machinery contractor. The rectifiers have to function perfectly under the conditions illustrated.







1224 kW mobile rectifier and substation specially designed for service with the Netherlands Railways.

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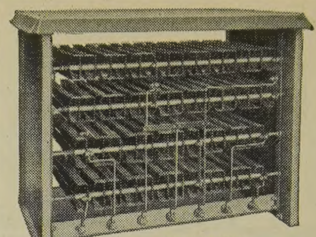

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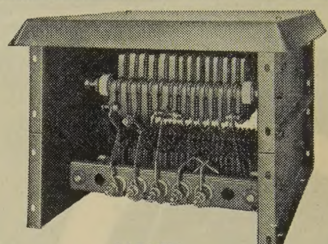

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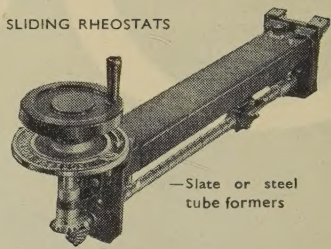

—Slate or steel tube formers

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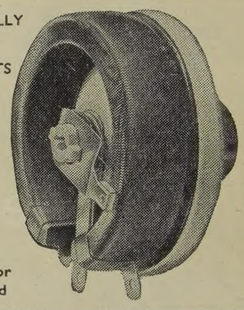

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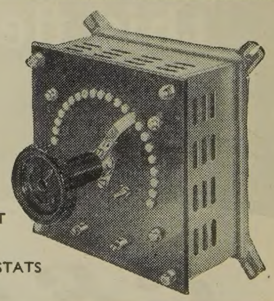

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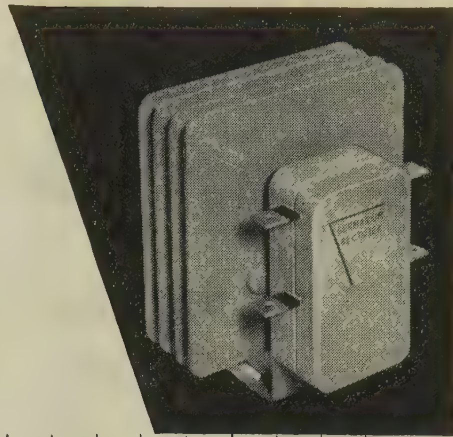

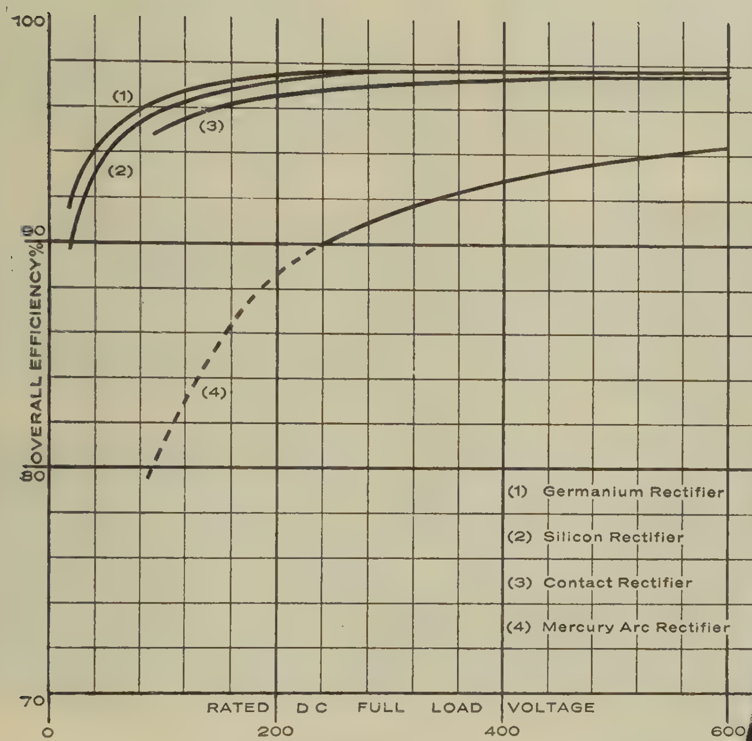

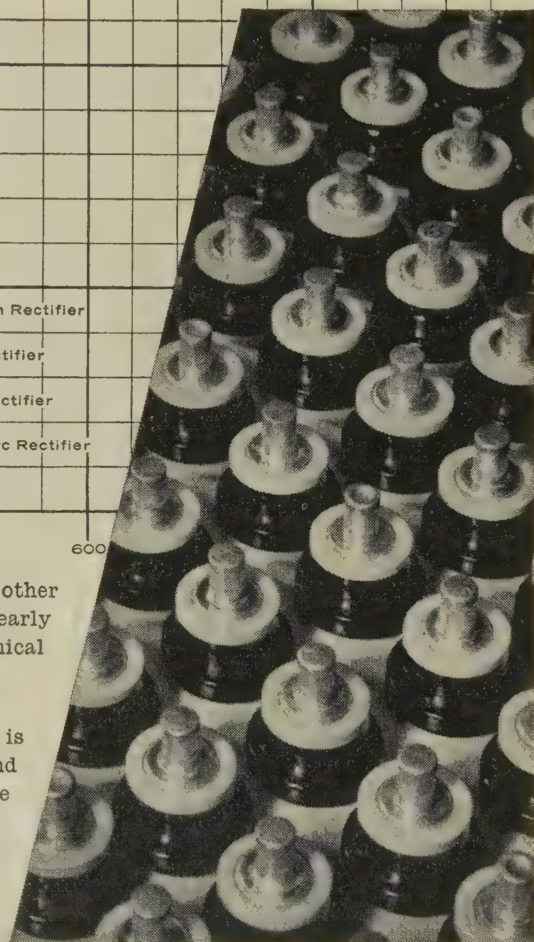

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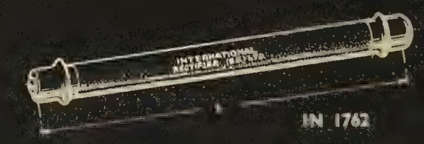
IN2374	GFIS2	1,000	250	100	3·0	10	100	0·5
IN2376	FFIF5	2,000	200	100	7·5	10	100	0·9
IN2379	FFIH10	4,000	100	50	15·0	10	100	1·25
IN2380	FFIT15	6,000	100	50	22·5	10	100	2·5
IN2381	FFIT25	10,000	75	25	37·5	10	100	2·5

JETEC Type	Int'l. Type	Peak Inverse Voltage, Volts	Max Rectified DC Output Current (ma) Oil Immersed Oil Temp. at 75°C	Max. Reverse Current at PIV at 25°C	Forward DC Volt Drop at Rated DC Current Volts	"L" Length Inches
IN1760	EFID40M	12,000	250	25	60·0	6·062
IN1762	FFID40M	16,000	250	25	60·0	6·062



For more complete technical information send for Bulletins SR-227 and SR-225-B.

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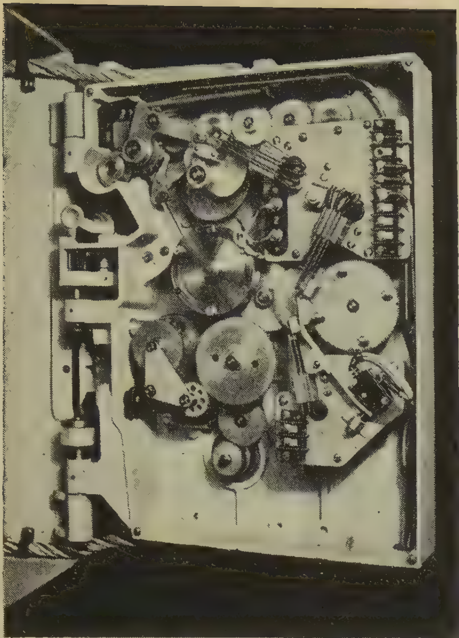
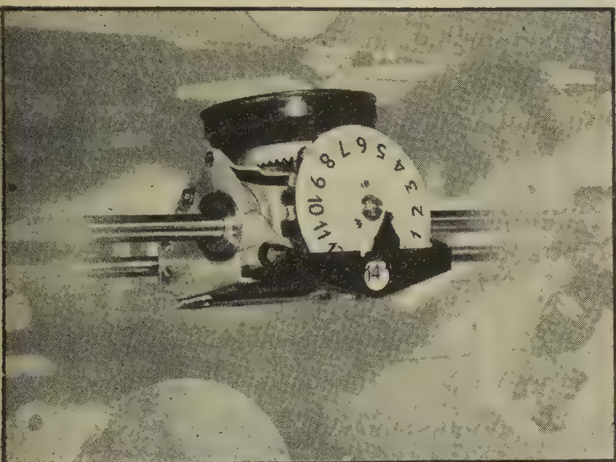


Chart-drive gear train and multi-point mechanism

This new *mark 3* electronic *multelec* recorder—



Multi-point printing mechanism with self-lubricating pen-carriage unit

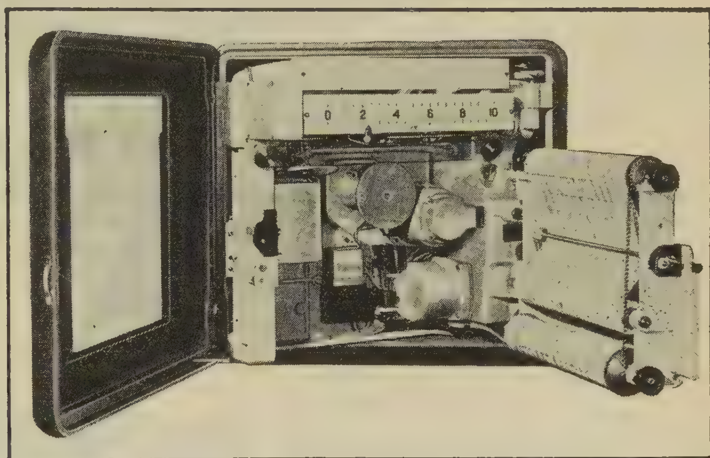
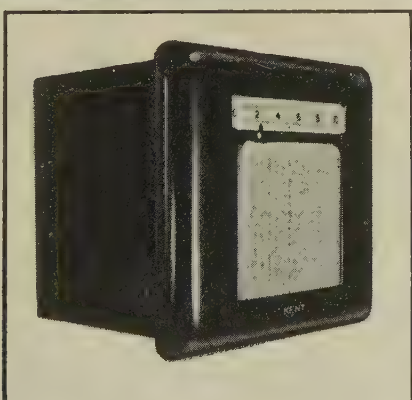


Chart frame swung away for ready access to main-frame components



Mark 3 Multelec recorder

—uses the same system and components as those in the electronic circular-chart recorder in the KENT *Commander* range. It retains, however, the same easy-to-read strip-chart (10 in. width) used in the *Mark* 2 *Multelec* instrument. The *Mark* 3 is available for the measurement of such variables as temperature, oxygen percentage, millivoltage, reactor power level, and—for certain applications—*Mark* 30 automatic control is included.

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- Wide choice of chart speeds, from ½ in./hour to 4 in./minute
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- Multi-point printing intervals of 5, 10 or 20 seconds, depending on application
- *Mark* 30 Series air-operated automatic control is provided when required (single-, 2-, or 3-term); also electric on/off control

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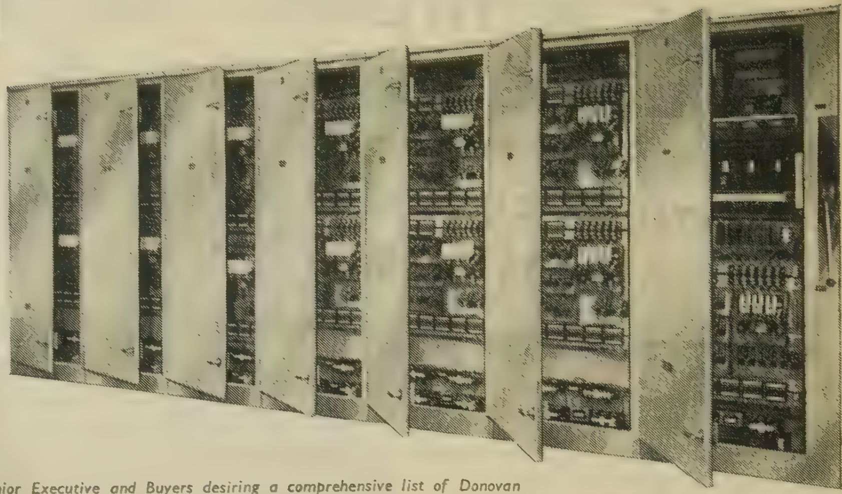

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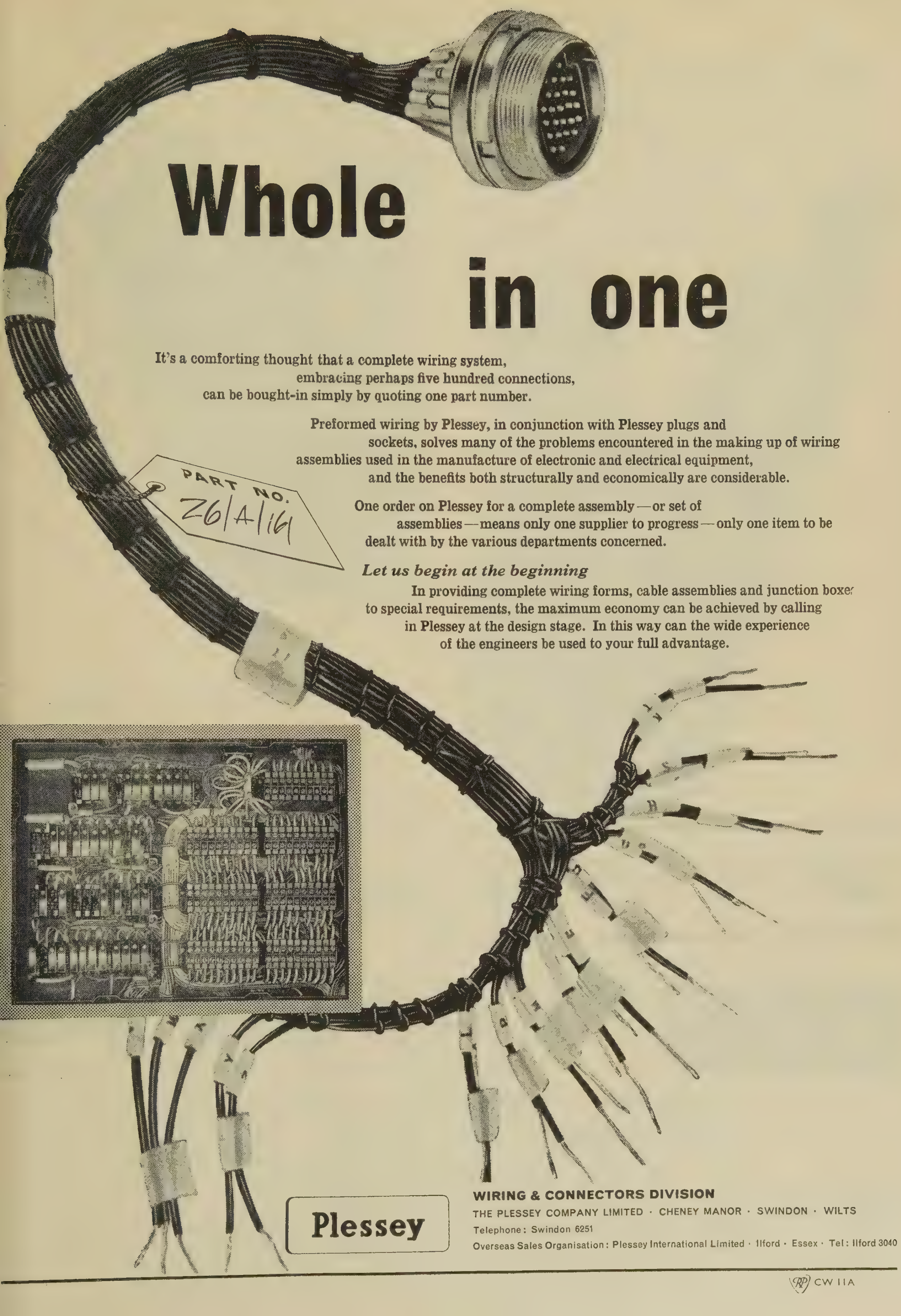

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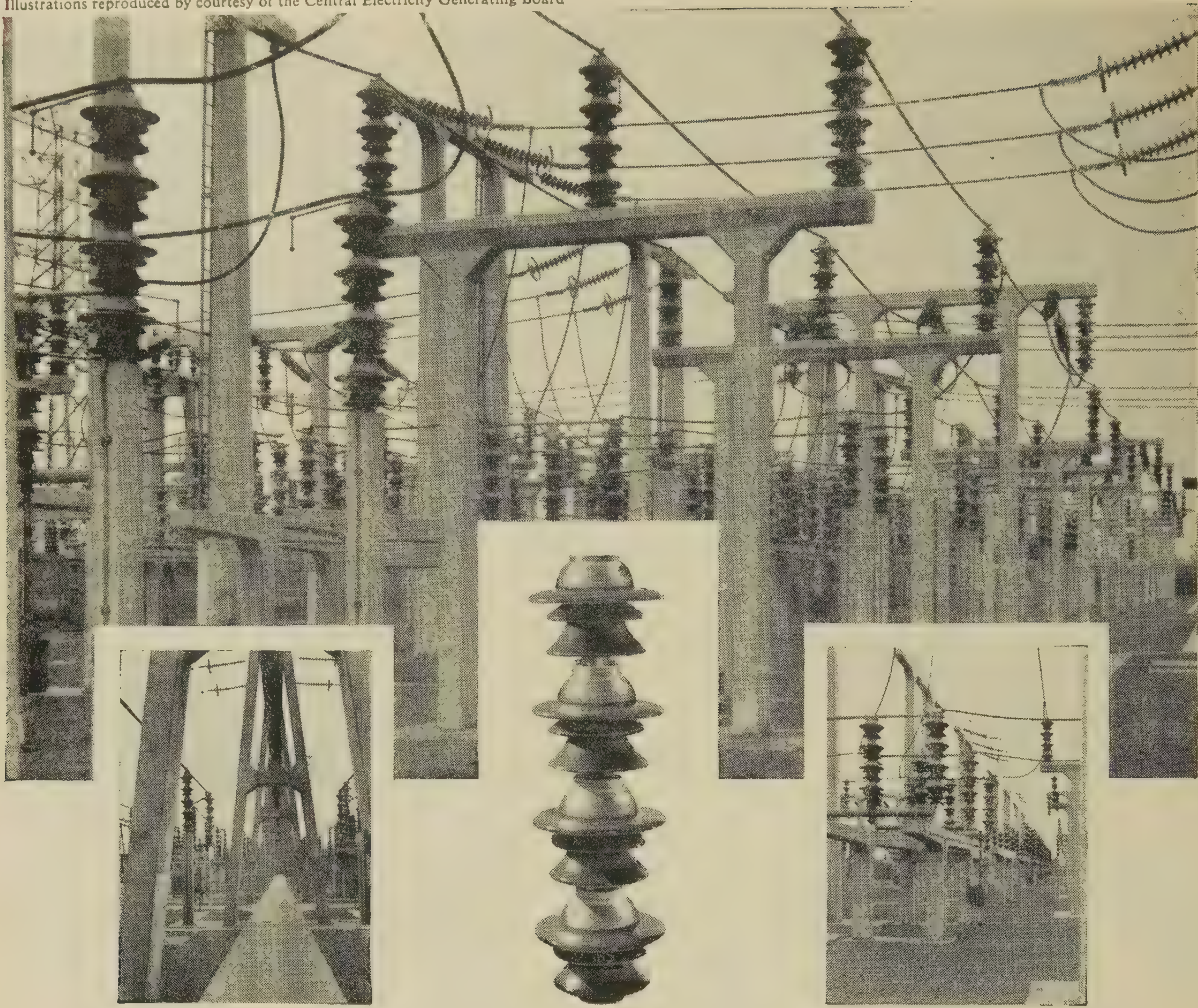

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EDITED UNDER THE SUPERINTENDENCE OF W. K. BRASHER, C.B.E., M.A., M.I.E.E., SECRETARY

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The Institution of Electrical Engineers
Paper No. 3133
Oct. 1959
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INAUGURAL ADDRESS

By SIR WILLIS JACKSON, F.R.S., President.

'THE MAKING OF PROFESSIONAL ENGINEERS'

(*Address delivered before* THE INSTITUTION, 9*th October*, 1959.)

INTRODUCTION

When I first entered the Institution building some 30 years ;o, I soon found myself looking at the tablets mounted at the trance to the lecture theatre on which are inscribed the names those who have been honoured by election to the Presidency our Institution—names which will be linked in perpetuity with e evolution of the manifold applications of electricity for the nefit of mankind. I am sure that many others must have been nilarly inspired to hope that they might one day be thought orthy to follow them. More recently I have come to regard ese names in a somewhat different light—not less as men of dividual distinction, but more as servants of The Institution; as en selected to perform for a short period a special duty symbolic the service to our profession being given by many others whose mes are not similarly displayed; by the members of Council d by the officers and committee members of the specialized ctions and Local Centres. These men are the backbone of e Institution. Year by year they support and sustain the esident, and like my predecessors I shall need all the help ey can give. I am deeply grateful for the honour which the embers of The Institution have done me, and I hope I may ove to justify it.

My predecessors have been representative of all branches of r profession—of industry and the public services, of its many ecializations in power and communication engineering and of foundations in research and education. In general it has en pretty clear which branch it was they individually repre- nted. With me it is not perhaps so clear, for formally and formally, officially and unofficially, I have dabbled at most. owever, all are likely to identify me with the preparation of ung people for careers in electrical engineering, and it is out the problems and responsibilities associated with this eparation that I want to speak.

When I began to prepare my address I had in mind, as a eliminary to the discussion of these matters, drawing some tailed technical comparisons between the situation which isted in electrical engineering when I joined the undergraduate urse at Manchester University in 1922 and that facing the rresponding present-day students of this subject. In the event I can include only a brief reference to the fantastic pace and scale of the progress which has taken place during the intervening period. In it there have been discovered and developed to the stage of large-scale production a great diversity of new forms of electrical equipment, of which some prominent examples are the pentode, the cavity magnetron, the klystron, travelling-wave tubes and solid-state devices among which the transistor is outstanding; television and radar; systems of short-wave, microwave, and long-distance submarine telephone cable, communication; electronic digital computers; closed-loop servomechanisms and other means of automatic control; new scientific instruments such as the electron microscope and the mass spectrometer, and a whole range of high-energy particle accelerators. In power engineering the changes have been no less outstanding, as exemplified by the development of the Grid, the production of turbo-generators some 10 times larger in capacity and 4 times less in weight per kilovolt-ampere than 35-40 years ago, and the evolution of the nuclear power reactor.

Much of this progress has been made possible by the development of many new magnetic, insulating, semiconducting and structural materials and of improved forms of previously existing ones, and these have also contributed, where applicable, to the considerable changes which have occurred in the types of long-established equipment—dynamos, motors, transformers, instruments, cables, transmission lines, etc.—round which the electrical part of my undergraduate course revolved.

The origins of many of these developments lie in realms of physics, chemistry, mathematics and metallurgy with which I, as a 1925 graduate, and indeed pre-war electrical engineering graduates in general, had the most superficial contact. For example, the concepts of electricity which had been presented to us as basic, and the electric circuit theory we had been taught to use with considerable facility, proved to be quite inadequate to provide an understanding, let alone an ability to initiate a solution, of some of the problems involved. We found ourselves obliged to replace what we thought were the basic principles governing the behaviour of transmission lines and thermionic valves, for example, by a set of more fundamental ones. There became available to us a whole range of new materials, evidently

of great potential importance to the progress of our work, the mechanisms of whose special properties we knew virtually nothing. We observed that the trend of our respective specialities could be profoundly affected by what was happening in other specialities with which we had little acquaintance. We found to our embarrassment that we could not be successful specialists unless we were good non-specialists. Few, if any, special courses were available to help us and we dealt with the rapidly changing situation as best we could.

We had to adapt ourselves, not only to the broadening scientific foundations of electrical development, but also to its changing pattern. More and more it involved the handling of major projects, and became a large-scale exercise in team work. It required the professional engineer, and indeed the scientist also, to penetrate more into the manufacturing and organizational fields than previously had been normal. There is nothing new, of course, in the statement that progress in an engineering career requires of the individual more than technical competence. What was new was the rapid increase in the number of men of whom more than technical competence was demanded by the character and the pace of technical development; the increasing occupancy of senior administrative positions by professional engineers and scientists, and the consequential inquiry by these men into means by which their junior colleagues might be prepared more effectively for these wider responsibilities.

Moreover, these wider responsibilities have extended enormously in scope if not in basic character. Engineering concerns the applications of science to the needs of man and society. It is therefore inseparable from humanism. The engineer is up to the neck in human problems whether he likes it or not. He is producing changes in man's mode of life over an extending range and with increasing speed and directness, and raising social problems the consideration of which must form an integral part of his technical and administrative thinking and decisions. It may rightly be said that this also has always characterized engineering activity. What is new in my time, and quite recently, is the explicit recognition and open discussion of the humanistic aspect of technology, and the deliberate questioning as to whether, and how, attention should be devoted to it in the preparation of professional engineers.

The argument may be extended still further. The high standard of living which we enjoy and are striving to maintain and improve, and the establishment of a defensive strength which we hope we shall never have need to attempt to demonstrate, are dependent on our export trade. In this we are engaged in a technological battle with countries which can draw on richer natural resources and can bring larger numbers of trained men to bear on defined scientific and technical objectives. It is a battle in which national prestige is now linked with priority of scientific and technical achievement, and where what is achieved, or is said to have been achieved, in one part of the world—or well outside it—is reported everywhere within a few hours. Our scientists and technologists have become not only the guardians and guarantors of our national economy but also the agents of a new diplomacy in which more than an expanding export trade is at stake. They have a direct part to play as teachers or advisers in the industrialization of the underdeveloped countries and must not only carry conviction as experts in their particular scientific and technical specialities but also gain respect as ambassadors of broad vision, sound judgment and unquestionable integrity.

Again, it may be said that this latter is no new role for the Britisher—the point is that it is a role in which our scientists and technologists must play an increasingly energetic and responsible part.

It is into this complex and diversified activity that we senior members of our profession, in company with our colleagues other branches of technology, are inviting a greater proporti of our most able young people. It is an activity which is wort of and needs the best. In so doing, however, we carry a hea share of the responsibility for ensuring that they are prope prepared by education, training and example for participati in it. I shall try to analyse some aspects of what is involved.

In approaching this we shall be wise to avoid the view tha since we older men succeeded in some measure in adjusti ourselves without much systematic help to the rapidly changi situation I have outlined, the newcomers can well be left to d the same. Those who take this view and act accordingly ma be quite certain that many of the newcomers will deal with ne situations as competently as they themselves did in the pas But they would be wiser to recognize that the starting-poi has changed enormously, that the demands are growing in sco and severity, and that with increasing numbers there is like to be a reduction in the average level of innate ability if n in examination results. All these demand a more prolonge preparation in education and training. I do not mean by thi however, an extended duration of undergraduate cours (though this may prove to be desirable before it is physical attainable) for reasons such as those expressed by Sir Richa Livingstone[1] in the remark

> If we wish to teach a subject, we must teach it at the age whe the mind can digest it. Otherwise we shall be like mothers wh feed their babies on beans and bacon. But there is another prin ciple, if not more important, even more commonly ignored. Th fruitfulness of education, at least in some subjects, depends o experience of life.

Engineering is one such subject. What I mean, therefore, that the treatment of the principles of physical and engineerin science on which undergraduate and similar courses must largel concentrate will need to be supplemented increasingly at appro priate later stages of experience. This will demand the pa ticipation as teachers of men whose primary activity is in th practice of engineering, and a much greater measure of collabora tion between the universities, technical colleges and industr than exists at present. Our limited present progress in thi connection, and other weaknesses of our educational system reflect our continuing tendency to regard the schools, th universities, the technical colleges and industry as separate com partments, and not as interwoven and interdependent elements in a continuous educational process. We in this Institution hav done a good deal and must do much more to change thi situation.

Most of the preceding and of what I shall say later relate to the making of professional engineers. Unfortunately this question is liable to obscure the importance of the supporting contribution and the needs in further education and training, of the much larger body of our technicians and craftsmen. It is too frequently overlooked that without their skill and resource no new idea can be translated from the laboratory and design office into efficient, reliable and economic engineering equipment. The satisfactory education and training of these men—and women— is no less vital to the successful operation of industry and the public services, and to the health of the national economy, than that of scientists and technologists, and in some respects it raises more difficult problems. I regret that space will not permit me to deal with them in this address.

THE SCHOOLS

Table 1 shows the response of the secondary grammar and public schools to the call of recent years that a larger number of our most able young people should prepare themselves for a

Table 1

Growth since 1938 of the Numbers of School Boys and Girls passing the Advanced Level G.C.E. Examinations in Physics, Chemistry and Mathematics*

Year	Physics			Chemistry			Mathematics†		
	Boys	Girls	Total	Boys	Girls	Total	Boys	Girls	Total
H.S.C.									
1938	Not available		3 153	Not available		3 035	Not available		3 224
1948			8 589			7 196			7 508
G.C.E.									
1953	9 654	1 275	10 929	8 087	1 454	9 541	8 185	1 156	9 341
1958	15 382	2 029	17 411	11 458	2 185	13 643	13 541	1 993	15 534

* Supplied by the Ministry of Education.
† Excludes Applied Mathematics and Mechanics.

olonged study of science and its applications. With this call is been associated the growth of a closer contact and under-anding between the schools and industry—between those io are moulding the thinking of young people and those sponsible for providing opportunities for them to pursue tisfying careers. This has occurred through vacation schools industry for masters and senior students; conferences repre-ntative of industry and the schools; the preparation of films picting scientific and technological progress; the issue of reer publications by the Press and of descriptive training ooklets by individual firms; and the establishment in 1955 of e Industrial Fund for the Advancement of Scientific Education the Independent Schools.

If, in taking these steps, the aim on the industrial side has en to ensure that more of the best students devote themselves the study of science, there has nevertheless been explicitly sociated with it a desire to avoid a degree of concentration ch as might frustrate the achievement of a broad general ucation. Certainly the Executive Committee of the Industrial ind had more in mind than a mere increase in the number of xth-form science specialists. They were anxious that this creased number should be more broadly educated than has en the case. At age 18 our sixth-form scientists are probably year ahead of their contemporaries anywhere in their knowledge science, but know correspondingly less about other subjects. ie same applies, but even more so, to the arts specialists, for iom only a modest attempt appears yet to have been made to ford an appreciation, limited though this may have to be, of e history and achievements of science and of the manner in iich its progress has affected the evolution of our communal e. I myself go a long way with Dr. James, Vice-Chancellor the University of Southampton,[2] in believing that

> the schools should endeavour to reach a situation in which the present design of studies in the Sixth Form is changed into one in which the child is not inevitably and finally committed to the arts or science side; in which education advances on a wider front, and the pupil's education, both in arts and science, goes on steadily, and as far as possible, as one thing and not as two.

My knowledge of secondary school teaching is too limited r me to be able to suggest how this objective might best be hieved. Much has been said and written by distinguished admasters during recent years. It has revealed the severity of e conflict between the claims of general education, not least to mpensate for the cultural poverty of the home background many of the young people now participating in sixth-form rk, and those of specialist study, for the purpose of per-tting the more able to grapple with difficult concepts within imited field. But it does not require a deep knowledge of the schools to recognize that changes in desirable directions are being impeded by two factors, at least, for which the schools cannot be accounted responsible.

The first is the shortage of well-qualified science teachers, the scale of which may be judged from the data of Table 2.

Table 2

Graduate Teachers in Mathematics, Physics and Chemistry in Maintained Secondary Schools providing G.C.E. 'O' Level Courses (October, 1958)

	Mathematics		Physics		Chemistry	
	Men	Women	Men	Women	Men	Women
Total in posts, October, 1958	4 461		2 070		2 375	
Net increase, 1957–58	93	81	123	1	134	38
	174		124		172	
Total vacancies and posts unsatisfactorily filled, October, 1958	511		217		111	

In comparison with the data of line 2 it is to be noted that, of the 1958 graduate (first degree) output in the above-mentioned subjects, 94 mathematicians, 177 physicists and 131 chemists accepted first appointments in the Government or public services or in industry, and that 118, 262 and 473 respectively elected to continue at the university for post-graduate work leading to higher degrees. Any expectation that a substantial proportion of the latter numbers may enter the schools in due course must unfortunately be restrained by the fact that, of those who left the universities with higher degrees in session 1957–58, only 2 mathematicians, 9 physicists and 15 chemists did so, compared with 14, 73 and 155 who joined the Government and public services and industry.

This is an untenable state of affairs and the consequences of a continuance of it will be disastrous. It is evident that in satisfying their need for more scientists the Government and public services and industry are incurring the grave risk of restricting the early scientific education of the greater numbers they are persuading to follow scientific and technological careers and of inhibiting its extension to all as an integral continuing part of general education.

The increasing magnitude of the problem may be judged from the data of Table 3, taken in relation to those of Table 1, which

show the Ministry of Education's estimates of the growth relative to 1959 in the number of 17-year-old students in the English and Welsh schools.

Table 3

Estimated Increase relative to 1959 in the Number of 17-Year-Old Students in Schools in England and Wales

Year	1959	1960	1961	1962	1963	1964	1965	1966	1967
Relative number of students ..	100·0	118·0	129·5	148·0	139·5	178·0	200·0	182·0	179·0

The easy comment is that the salaries of graduate science teachers should be made more commensurate with those attainable in other forms of Government service and in industry. In times of shortage within a free society this is an elusive argument. In fact salary is by no means the only consideration affecting the willingness of graduate scientists to enter school teaching work. Of comparable importance is the improvement of teaching facilities and amenities, including the more generous provision of laboratory assistants, such as has been achieved in part with the aid of the Industrial Fund and as is now being extended by the Ministry of Education to the maintained schools. And professional men like ourselves can make a vital psychological contribution by seeking opportunities to give recognition to the great national importance of teaching work at all levels and by helping to raise the status of the teaching profession in the eyes of the general public. I return to the shortage of teachers in later Sections.

The second factor is that a broadening of sixth-form curricula can be made only with the collaboration of the universities, and there is all too little evidence of an active pursuit of such a collaborative effort. Regrettable though this may be, it is easy to understand. Such a change within the schools would involve a lowering of the present high standards of knowledge in specialist subjects required for university entry, which is in the wrong direction to assist the universities to withstand the pressure of new knowledge within these subjects. It would also increase the already considerable difficulties of selection. An increase in the duration of undergraduate courses from three to four years would be regarded as essential, only to be ruled out as unattainable in circumstances where the plans for university expansion will no more than cater for the increased numbers of new students to be expected from the data of Table 3.

The situation within the grammar and public schools is beset with difficulties and the changes which many regard as urgent may be slow in maturing. Unfortunately there are evidences of movement within some grammar schools in the reverse direction. I have in mind the introduction of engineering subjects into sixth-form curricula, no doubt with the aim of stimulating the interest of some students in engineering as a career, and of providing an incentive to serious study. In my opinion it would be a great misfortune if, through a misconception of the educational needs of the professional engineer, the grammar schools were to encourage boys with little aptitude for mathematics and the basic sciences to remain at school to age 18 for the study of technical subjects. These boys should leave to enter industry at an earlier age and to pursue their studies at a technical college. The profession of engineering is no haven for the scientific weakling.

THE UNIVERSITIES

As a preliminary to consideration of the problems which face the universities, it is necessary to review the recent expansion of their activities.

Table 4 shows the growth in the number of full-time students by faculties since 1938–39 and the fact that by 1958–59 the numbers of students of pure science had increased by a factor of 3·00 and of technology by one of 2·83, and that combined they now comprise about 38% of the overall university student population. The expected further growth for which the University Grants Committee is seeking to make provision is to an overall figure of 124 000 by the mid-1960's, of whom some 55 000 are expected to be students of science and technology, as compared with the present figure of about 38 000, with a larger

Table 4

University Student Numbers

(supplied by the University Grants Committee)
Numbers of full-time students by faculties

Faculties	Academic years							
	1938–39		1948–49		1953–54		Autumn term 1958	
	Number	Per cent	Number	Per cent	Number	Per cent	Number	Per cent
Arts ..	22 374	44·7	37 147	44·4	34 673	43·0	42 739	42·9
Pure science ..	7 661	15·3	16 099	19·2	16 971	21·1	22 949	23·1
Medicine ..	11 883	23·8	13 718	16·4	13 239	16·4	12 688	12·8
Dentistry ..	1 488	3·0	2 547	3·0	2 564	3·2	2 980	3·0
Technology ..	5 288	10·6	10 884	13·0	10 036	12·4	14 942	15·0
Agriculture and forestry ..	1 043	2·1	2 919	3·5	2 066	2·6	2 032	2·0
Veterinary science ..	265	0·5	376	0·5	1 053	1·3	1 206	1·2
Total ..	50 002	100·0	83 690	100·0	80 602	100·0	99 536	100·0

Table 5

POST-GRADUATE UNIVERSITY STUDENTS
(supplied by the University Grants Committee)

	1938–39	1948–49	1953–54	Autumn term 1958
Science	1268	2429	3290	3853
Technology	388	858	1318	1916
Total in universities	3094	6452	9468*	11062*

* Total excludes students working for a Teacher's Diploma.

roportionate increase in technology than in science. Table 5 ves the growth of post-graduate student numbers with parcular reference to those in science and technology.

Undergraduate Courses

In the preceding Sections I have referred to the pressure on ndergraduate courses which is being generated, on the one and, by a growing recognition that the work of the sixth forms t school—and also of the undergraduate courses themselves— too specialized, and on the other, by the extremely rapid xpansion of knowledge in specialist fields, particularly within cience and technology. As already mentioned, the simple nswer to both would be to increase the duration of underraduate courses by a year, and some would find further justificaon for such a change in the greater length of the corresponding ourses in Continental countries. For the majority of students, owever, most of all for those of technology, three years at a niversity is a long enough preliminary to active participation in ne affairs of life outside. Of greater urgency is the need for the niversities to rethink the objectives and content of their present ree-year courses, and for them to consider co-operatively mong themselves, and in consultation with the technical colleges nd industry, their distinctive contribution to post-graduate udies for a proportion of the graduate output. This is made articularly necessary in the field of technology by the developnent within the technical colleges of courses leading to the new Diploma in Technology and by the recent announcement of a igher award, that of Membership of the College of Techologists, to which I refer in the next Section.

I appreciate in respect of undergraduate courses in electrical ngineering that much has already been done to remove or reduce ttention to many of the technicalities which used to find a lace in them. My doubt concerns whether enough recognition as yet been given in these courses to the dependence of progress electrical engineering on the work of physicists, chemists, athematicians and metallurgists, and to the outstanding nportance of the development and exploitation of new materials. The teaching of the subject of electrical machines, and of electroechanical systems generally, is particularly in need of reconderation with a view to making it as stimulating and searching study as that of electronics and communications and to orrecting the unbalance of student interest in favour of the atter which has prevailed for some time. Still better, to show ow the two are interrelated through the principles of electroagnetism and the properties of materials, and bound together y a common mathematics. Considerable initiative is being aken in this matter within the Electrical Engineering Departnent of the Massachusetts Institute of Technology, where the iew is held that the analysis of electro-mechanical systems in erms of steady-state concepts using equivalent circuits and etwork theory does not afford a sufficiently progressive pproach to the problems of electromagnetic energy conversion, and that there may be merit in starting from the complete equations of the most general system derived from Hamilton's principle, energy considerations and field theory and in teaching the student to deal with particular cases by the introduction of appropriate simplifications into the general case.

I do not underestimate the difficulties—the best method of approach will not be easy to find. I know it will be said, from personal experience of similar attempts, that undergraduate courses which drew as extensively on science and mathematics as I am suggesting would be unattractive to students who, having chosen engineering rather than science, expect their course to introduce them to the practice of their chosen subject and to permit some concentration on a specialist branch of it in the final stages. What I visualize is no contradiction of this expectation. The problem is how to broaden the fundamentals without making, or appearing to make, these fundamentals an end in themselves; and how therefore to illustrate their technological significance by examples drawn from developing practice as a bridge between scientific abstraction and real engineering.

The desirable result will not be achieved merely by the incorporation of specific courses in physics, chemistry, mathematics and metallurgy, taught, in a manner apart, in the sense of the honours schools in these subjects. Nor, of course, must the treatment of their appropriate parts carry with it the stigma which I have known to be associated with courses designated 'for engineers' mainly because the scientists and mathematicians concerned were inclined to regard them as a provision for second-rate minds rather than for first-rate ones whose interests lay in the application of these subjects, as distinct from the pursuit of them for their own sake. The attitude of intellectual superiority which has too often characterized the contribution of scientists and mathematicians to engineering education has been a major factor in delaying the emergence of engineering to the status it is now coming to occupy as a subject of university study, and as a pursuit worthy of, and needing, a substantial proportion of the best brains available. The trend of university education in electrical engineering which I believe to be desirable will demand a fuller measure of inter-departmental collaboration and a less rigid adherence to traditional departmentalism within science and technology than has existed in the past, and than appears still to characterize too many of our universities.

Even then the full potentialities of a university education will not have been realized unless the student's mind has been opened to an appreciation of the fact that exclusive devotion to a scientific discipline will not give him all he needs as a preparation for life. With this as his theme, Sir Eric Ashby has presented the case for an extension of inter-departmental collaboration beyond science and technology into the domain of the arts faculties in a stimulating paper entitled 'Technological Humanism'.[3] In this he says,

> If technologists are to enter fully into their responsibilities in the world of tomorrow, they have to adapt themselves to novel technologies; they must also be able to adapt themselves to the social consequences of the novel technologies. To pursue technology in a spirit of liberality, they need not only a thorough training in the theory and practice of technology; they need also an understanding of men and communities such as is acquired through literature and history and the social sciences.

And he gives examples of the type of course which he considers should be made available to students of technology by the faculties of arts.

Some universities have already taken steps in this direction, and I hope others will follow. I am naturally particularly aware, for example, of the scheme of lunch-time lectures at the Imperial College of Science and Technology, and of the opportunity available to the final-year undergraduates of this College to spend a day per week at the London School of Economics. In

my opinion, however, experiments such as these will be really successful only if the teachers of technology provide a bridge, by themselves constantly referring to and illustrating the humanitarian aspects of technology in the presentation of their respective subjects. And it should not be overlooked that perhaps the most liberalizing influence of all is active participation by the student in the corporate life of the university.

Post-Graduate Courses and Research

Movements in undergraduate engineering education in these directions will, of course, leave for later acquisition an increasing amount of more specialized knowledge. With varying degrees of relevance to different men, this concerns the advanced aspects of the engineering science of their chosen field, the techniques of the various specialized branches of it, the materials on which the successful exploitation of these techniques are based, and the use of the analytical tools which are now available for the solution of complex engineering problems.

Until quite recently the acquisition of this supplementary knowledge was left largely to individual effort and initiative, and little provision was made in the form of post-graduate courses for its systematic presentation. However, several university engineering departments are now providing courses of one year's duration on subjects related to their particular research interests; the larger technical colleges are organizing part-time, mainly evening, courses in subjects of special relevance to the industries of their respective regions; and in some industrial concerns lecture courses and discussions on technical and organization matters form an integral part of their graduate training schemes. It is beyond question that the need for such courses will grow and that participation in them must be recognized and accepted as an increasing necessity.

In respect of the university provisions, I hold the view that participation in them should desirably be preceded by a period of industrial training as a foundation for the reliable choice of a specialist field, and so that the graduate may gain an appreciation of the grounds on which existing practices in his chosen field have emerged and of the directions in which improvement is required. I am aware that many of the university staff members concerned also hold this view; that they are disappointed with the response of industry to the steps they have taken; and have concluded that the only means of ensuring adequate support for their courses is to accept as students men who have just graduated.

The limited response of industry has been due in part to the shortage of graduates at a time of rapidly expanding industrial activity, and I hope that the situation will improve with the increasing annual output of graduates and with the termination of the National Service arrangements. But in part the universities are themselves responsible.

In the first place it would have been wise, in the circumstances just mentioned, had they not all adhered so rigidly to the normal sessional pattern of university courses, but had been willing to offer, as an initial step, courses of shorter duration. Secondly, some of the courses offered have been essentially departmental in character, have not drawn on the wider resources of their university, and have therefore failed to reflect the kind of interrelationships within science and technology to which I referred earlier. And thirdly, there has been some reluctance to recognize the need at this level for the participation of outside experts as lecturers. In this respect I believe we have something to learn from other countries in which, for limited periods, carefully selected men whose primary employment is in industry or Government establishment are given academic status and contribute to the advanced specialist teaching on a part-time basis. It is quite unrealistic to suppose that the teaching of technology at its highest level can be carried wholly, or largely, by men who occupy full-time teaching posts, unless these men return to industry or a similar environment at appropriate intervals. In my opinion the raising of technological teaching in this country to the level required demands a much greater mobility of staff between educational institutions on the one hand and industry or Government establishment on the other than has yet been achieved, and, in supplementation, that carefully selected men should be fully recognized members of both, as is already the case in medicine. A good start would be for the research establishments of the Department of Scientific and Industrial Research, and some of the research associations, to be accepted by the appropriate universities as recognized institutions in this sense. The separation of the D.S.I.R. establishments from the domain of technological teaching, and the lack of a recognized link between them and the universities in respect of scientific and technological research, are national handicaps of great seriousness which should be removed as quickly as possible.

The universities have experienced considerable difficulties in recent years in obtaining as full-time staff members of their engineering departments a sufficient number of men who are leaders, or potential leaders, of thought in their subject and also keen and capable of teaching it. The difficulty arises basically from the fact that, in deciding to take up the study of engineering, a young man is motivated, generally speaking, by the desire to practise, not to teach, it. His entry into teaching work usually involves, therefore, a withdrawal from practice under circumstances where, at present, the practice affords considerable attractions. Salary is perhaps most frequently quoted in this respect, but while it would be idle to deny the significance of this in some cases, it is often overstated in the light of recent salary changes, and of the possibilities, for the best men, of outside consulting work. Of greater moment may be the limited flexibility of industrial superannuation schemes in respect of the transferability of pension rights. But the difficulty goes deeper. For men with engineering in their blood the practice of it, particularly at times of rapid technological change and industrial expansion, is a highly stimulating experience and one which affords considerable scope for the exercise of initiative and the carrying of responsibility. The problem is how to marry this situation to the need, in the larger technical colleges as well as in the universities, for more forward-looking teachers of technology.

In general, first-class men will not be attracted, nor will they remain first-class and maintain a vital environment for their students, unless they are afforded the opportunity of pursuing research work. It is therefore gratifying that the Department of Scientific and Industrial Research has now been provided with augmented funds for the support of research programmes of special timeliness and promise. The dangers are that the pursuit of research in specialist fields may become a dominant interest, at the expense of attention to the broad educational needs of the undergraduate student body and of adequate personal acquaintance with the individual members of this body; and that the attempt to synthesize new knowledge and to unify it with the old for teaching purposes may be neglected because it does not carry the same glamour nor gain the same recognition as research (as normally understood). Moreover, the retention of raw graduates, for participation in limited research programmes, tends to generate in these young men an inability to recognize on their entry into industry that research work is not a thing apart, but something which, to be effective, must be woven into the whole fabric of industrial activity; and that it requires of the researcher experiences which cannot be gained in isolation from this wider environment. It is this

ind of consideration which prompted the conception of the lembership of the College of Technologists award to which refer in the next Section.

I recognize that much has been done within the universities owards attainment of the objectives I have tried to develop in nis Section. I also recognize that it is a good thing for there o be differences between universities, even substantial ones. ut there seems to me to be great need for systematic inter-niversity discussion at faculty level, not only in the direct nterests of the universities themselves, but also because col-boration with industry and Government establishments would e facilitated and strengthened thereby, and because they would e the better able, as in the national interest I believe they hould, to assist the colleges of advanced technology to formulate ne distinctive contribution to technological education which it hoped they will make. A clarification of the position which nese colleges are to occupy in the structure of technological ducation may soon become a matter of urgency.

THE TECHNICAL COLLEGES

Prior to the late war the only means open to the vast majority f young people who entered industry direct from school and ho wished to acquire the knowledge and qualifications which ney saw to be necessary for their progress was attendance at vening classes. These classes remain a very important, and ndeed a growing, part of further education, but by themselves ney are no longer adequate to provide for the technical needs f developing industry, let alone for the needs of the individual or continued general education. There has been a gratifying ncrease since the war in the willingness of industry, and of the ectrical industry in particular, to release its young employees o attend part-time day courses. Their number increased from 1 460 in 1938 to 434 672 in 1958, but very wide discrepancies xist between different industries in the granting of this facility, nd there is much scope for further improvement. In its White aper on Technical Education (February, 1956), the Government et 700 000 as its target for the number of part-time day students y the early 1960's, and it is to be hoped—though there is reason o doubt—that this figure will be achieved.

Table 6 shows the scale of development of Ordinary and

Table 6

ROWTH SINCE 1938 OF STUDENTS QUALIFYING FOR ORDINARY AND HIGHER NATIONAL CERTIFICATES*

Subject	1938		1958	
	O.N.C.	H.N.C.	O.N.C.	H.N.C.
Electrical engineering	917	379	4 271	2 165
Mechanical engineering	1 449	502	8 599	3 926
Production engineering	—	—	—	542
Civil engineering ..	—	—	—	278
Building	544	137	1 597	929
Chemistry	151	62	1 437	852
Applied chemistry ..	—	—	22	30
Chemical engineering	—	—	—	61
Applied physics ..	—	—	405	169
Metallurgy	—	—	373	269
Naval architecture ..	16	—	100	47
Textiles	104	57	129	49
Mining	—	—	715	205
Mining surveying ..	—	—	—	118
Commerce	132	—	380	7
Total	3 313	1 137	18 028	9 647

* Supplied by the Ministry of Education.

Higher National Certificate courses since 1938. These courses are now largely operated on a day-time basis, and this has reduced the wastage previously associated with evening study. But the wastage is still very large. The basic reason is that many of the boys admitted to the early years are unsuited to this type of course. They enter with their eye on the fact, as shown in Table 7, that National Certificate courses have been a major

Table 7

ANALYSIS OF MEANS OF COMPLIANCE WITH THE EXAMINATION REGULATIONS OF THE INSTITUTION 1954–58 INCLUSIVE

Calendar year	Degree	Diploma or Associateship	Via National Certificate	Institution Examination	Miscellaneous	Total
Elections and Transfers to Graduate Membership						
1954	469	179	707	126	6	1 487
1955	448	144	770	59	2	1 423
1956	580	179	1 101	81	9	1 950
1957	627	171	1 413	26	3	2 240
1958	587	158	947	19	3	1 714
Direct Elections to Associate Membership						
1954	103	12	87	24	15	241
1955	80	14	68	18	20	200
1956	135	19	115	28	23	320
1957	128	13	111	23	27	302
1958	130	22	112	8	24	296

route to exemption from the examination requirements of the professional institutions, and are inclined to attach little value to other courses, much more suited to many of them, which lead to technician and craft qualifications of the City and Guilds of London Institute and similar examining bodies. So much so that, having failed, too many withdraw completely from further study. No doubt the situation will be improved by the clarification of the structure, and of the interrelationships, of courses at the preliminary stage which is now occurring. But basically its solution demands of industry a much clearer recognition of the value which attaches to success in technician and craft courses, and closer collaboration with the technical colleges in the encouragement of its apprentices to participate in them.

The normal duration of day-time release from employment is one day a week for about 36 weeks per year. On this basis, with some evening work at college added, satisfaction of the examination requirements of the various professional bodies is becoming an increasingly difficult undertaking. With our own Institution it now involves a minimum of eight years from entry to the first year of the Ordinary course. Even then the sequence of scientific and technical subjects is not best suited to professional purposes. Moreover, devotion of the whole period of college attendance to scientific and technical study affords no opportunity for participation in the corporate life of the college, and no time for the continuance of general education except in so far as good teachers may achieve something of this within the scientific and technical subjects themselves.

These limitations have been overcome by the sandwich arrangements which characterize the new Diploma in Technology courses administered by the National Council for Technological Awards. Their normal structure is of alternate periods of six months in industry and in college over a four-year period, with entry based on an average mark of 60–70% in the Ordinary National Certificate examination, or Advanced Level G.C.E.

passes in mathematics and physics or chemistry, plus four passes at the Ordinary G.C.E. level.

Table 8 gives the number of students who were pursuing Diploma in Technology courses during the 1958–59 session.

Table 8

NUMBERS OF DIP.TECH.(ENG.) AND DIP.TECH. STUDENTS SESSION 1958–59

Subject	Number of students				
	First year	Second year	Third year	Fourth year	Total
Dip.Tech.(Eng.):					
Electrical engineering . .	358	299	143	67	867
Mechanical and production engineering	361	274	127	40	802
Civil engineering . .	23	3	2	—	28
Chemical engineering . .	37	22	2	—	61
Instrument and control engineering	10	9	—	—	19
Aeronautical engineering	64	22	—	—	86
Building	8	—	—	—	8
Dip.Tech.:					
Applied biology . .	9	6	—	—	15
Applied biochemistry . .	5	—	—	—	5
Applied pharmacology	5	—	—	—	5
Applied chemistry, Chemical technology, Industrial chemistry	103	58	34	9	204
Mathematics	40	14	—	—	54
Metallurgy	32	34	26	6	98
Physics	116	88	47	15	266
	1171	829	381	137	2518

Of these, some 35% had entered from Ordinary National Certificate courses. Success in the courses in electrical engineering so far approved by the National Council will afford complete exemption from the examination requirements of The Institution, and it is to be hoped that this will apply to all further courses which are similarly approved. As indicated in a joint statement[4] by the Ministry of Education and The Institution, published in 1958, it is likely that there will also be an increasing provision of similarly organized sandwich courses with a somewhat lower standard of entry and of attainment leading to Higher National Diplomas and partial exemption from The Institution's examination requirements.

These developments, in association with the trend for academically promising boys to remain at school beyond the statutory leaving age, suggest that in due course the great majority of prospective professional electrical engineers will either not enter National Certificate courses or will leave them at the Ordinary Certificate stage, and that these courses will come to serve mainly the needs of high-grade technicians, as was the conception when they were introduced some 30 years ago. The Institution has no intention, however, of closing this route to professional recognition. There are always likely to be some men of professional ability for whom, because of their inclinations or domestic circumstances, or because they are unable to arrange with their employers for their participation in a sandwich course, this will be the only route. The Institution has been criticized for too rapid an introduction of its new examination regulations to the embarrassment, reflected in the 1958 figures of Table 7, of many men now engaged on National Certificate courses, and I am sure it will be the wish of all of us to minimize such hardship as may arise during the transitional period.

When inaugurating the Diploma in Technology scheme the National Council for Technological Awards declared its intention to establish for the Dip.Tech and Dip.Tech.(Eng.) awards a standard comparable with that of an honours degree. This comparison inevitably raised the question as to what were to be the distinctive features of diploma in technology and degree courses. It was obvious that they were structurally different, and the significance of this was emphasized in the National Council's statement that the periods of industrial training were to be regarded as just as much a part of the course as those of college study, and that the two parts should be closely co-ordinated. An important factor in this concept was that in general the students would be 'industry based'; that is, they would be attached to sponsoring industrial concerns as student apprentices and these concerns would therefore act in partnership with the college in the achievement of this co-ordination. I shall refer to this matter in the next Section. A second distinction was the National Council's insistence on the inclusion of liberal studies within the curricula. What has not yet emerged explicitly is whether there are to be two distinctive approaches to the teaching of the technological subjects themselves; whether in fact there can or should be for men aiming at the same professional objective. It is easy to say, with the sandwich character of the diploma courses in mind, that the presentation in these courses should be more closely related to practice in the subject of which the student is gaining interwoven industrial or allied experience. The difficulty lies in defining what this means without contradicting the necessity, which I have already elaborated, for the teaching to prepare the student for a future, not merely for the present, situation. The broad distinction in method I myself would draw is that the diploma courses should tend to work from the particular towards the general, and degree courses from the general to the particular. Changes in university undergraduate courses in the directions discussed in the preceding Section, while the diploma courses are establishing themselves on their present lines, would contribute considerably to the drawing of this distinction. I do not see, at the moment, why the two approaches should not provide comparable intellectual disciplines. The matter affords much scope for educational research of which far too little is being done within, or if done, being published by, either the universities or the technical colleges. A number of well thought out papers on it would be a welcome and valuable addition to the literature of The Institution.

I remarked previously on the need for supplementation of our 3-year undergraduate courses by systematic post-graduate studies. The same arguments apply to the 4-year Dip.Tech and Dip.Tech.(Eng.) courses, which many feel should soon be extended to 5 years. In this case, accommodation, within the colleges of advanced technology at any rate, is unlikely to be the restraining factor. More important considerations are likely to be staffing and the possibility that firms which are at present financing students throughout a 4-year course may be unwilling to give them longer support. However, whether linked directly to an extension of Dip.Tech. courses or not, it seems evident that the larger technical colleges must come to organize full-time advanced courses of appropriate duration in the specialist fields of technology relevant to their respective regions, in supplementation of the advanced evening courses they are already providing.

Developments along these lines will have a special significance to the recent decision of the National Council for Technological Awards to institute an award higher than the Diploma in Technology, that of Membership of the College of Technologists. This award will normally be made for a programme of work successfully carried out jointly in industry and at a college, and

gistration for it will be available to university graduates as ell as to holders of the Dip.Tech. or Dip.Tech.(Eng.). The ogramme may be concerned with any technological aspect of dustrial activity—for example, research, development, design, oduction or market investigation—and submission for the vard may be made three years after approval of the project id registration as a candidate, provided a high proportion of e candidate's work in industry has been devoted to the project id this work has been adequately supported by college study. particularly important feature of the scheme is that the ndidate's work will be supervised jointly by staff members of e industrial organization concerned and of the college at hich the advanced study, or, where appropriate, some of the search, is to be undertaken. This serves to emphasize the oint made in the announcement of the scheme that 'the integraon of academic study and industrial training is an important ature of courses leading to the Diploma in Technology, and e Council feel that a similar collaboration between industry id college should be extended into the post-diploma field'. would add that this is another field in which there is need for oser collaboration between the larger technical colleges and the iversities if most effective use of staff and facilities is to be isured.

In the preceding Section I referred to the staffing of the iversity departments of technology. The needs of the techcal colleges in this respect were reported upon in 1956 by a oecial Committee of the Ministry of Education,[5] and Table 9 reproduced from the report.

This augurs well for an improvement in the standard of technical college teaching of which the universities might wisely take note. The second is the prospect of the early establishment of a residential staff college in which technical college teachers and representatives of industry, Government establishments, universities and the schools could examine and discuss together the aims and methods of technical and technological education in the light of experiences and developments in these related fields. The third concerns the need for the lively participation of senior industrial representatives in the government of technical colleges. Strong governing bodies and active advisory committees are vital to the development of a closer partnership between them and industry and to the necessary improvement in their status and staffing.

THE TRAINING OF PROFESSIONAL ELECTRICAL ENGINEERS

The preceding three Sections have dealt with certain aspects of the contributions of the schools, universities and technical colleges to the education of technologists. The major Engineering Institutions have always held the view, and have recorded it in their bye-laws, that for the adequate preparation of professional engineers this education requires to be supplemented by a further process, normally conducted in the environment of engineering practice and referred to as 'training'. The need to use this distinguishing word in relation to prospective professional engineers is perhaps unfortunate, since it is responsible for a

Table 9

Estimated Net Annual Increase and Gross Annual Recruitment of Full-Time Teachers in Technical Colleges required over the Five Years 1956–61

	Total number employed 1955–56	Total number of extra teachers required by 1960–61	Annual averages			
			1952–55		1956–61	
			Net increase	Gross recruitment	Net increase required	Gross recruitment required
All full-time teachers	11 455	7 160	770	1 300	1 430	2 300
Teachers of professional courses in science and technology:						
Mathematics and science graduates	(2 250)*	1 260	200	300	250	400
Technology graduates	(1 250)*	1 325	90	150	265	360
Graduate-equivalent	(900)*	190	75	120	40	100

* Not accurately known, but estimated from Ministry statistics for 1954–55.

The latest figures available show that during the 1957–58 ession there was a net increase of about 1 500 in the overall umber of full-time teachers as compared with the estimated verage annual requirement of 1 430; that the estimated annual ain of 250 mathematics and science graduates was just met; ut that the number of graduate teachers of technology increased only 150 as against the requirement of 265. Since the latter gure was also not met in 1956–57, there is an accumulating eficiency in respect of this category of teacher, and the position the senior lecturer and reader levels gives particular cause for nxiety.

There are three other matters which I feel I must mention. ne is the gratifying increase which is occurring in the number f suitably qualified candidates for entry to the technical acher training colleges as a preliminary to technical college opointments, and the recent decision of the Ministry of Educaon to expand the facilities of these colleges considerably.

widespread misunderstanding abroad of the essentially educational objectives involved. In respect of our own branch of the profession, these objectives are broadly to ensure:

(i) A sound knowledge of the properties, uses, limitations and methods of handling of the conducting, insulating, magnetic and structural materials employed in the construction of electrical equipment.

(ii) An appreciation of the nature and interrelationships of the main functional aspects—research, development, design, manufacture, sales, installation and operation—of electrical engineering activity, and of the respective contributions which need to be made to them by professional engineers, technicians and craftsmen.

(iii) A comprehensive acquaintance with the various facets of a selected specialist field and of other related ones on which the practice in it is dependent.

(iv) An understanding of the reasons, administrative and economic as well as technical, for present practices, and an enthusiasm to search for the directions in which improvements might most profitably be pursued.

Over many years The Institution has had Examination Regulations governing its educational requirements for Graduate Membership. These are about to be supplemented by Training Regulations, and candidates for Associate Membership will be required to submit a certified statement detailing the manner in which they claim to have satisfied these regulations. It is expected that this statement will often be submitted by Graduate Members some time prior to their application for Associate Membership with a view to obtaining an evaluation of their training, and, when completed, registration of the fact that it has been accepted as satisfactory. In respect of university students the normal procedure for meeting the requirement will be by post-graduate training of two years' overall duration, inclusive, where appropriate, of training obtained during long vacations and of periods spent in attendance at courses of advanced study. In some cases 9–10 months of the 2-year period will have been completed between leaving school and entering the university. I myself wish that this 1 : 3 : 1, or thick sandwich, arrangement could be made more general. For holders of the Dip.Tech.(Eng.) it should be met by the training they will have received during the industrial periods of the sandwich course, supplemented by the final phase of training normally provided for in student apprenticeships. While the position of those who have satisfied the Examination Regulations wholly by part-time study cannot be stated so clearly, the overall duration of their apprenticeships will usually have been much longer than for either of the previous categories, though the pattern and content may sometimes not have been ideal for professional purposes.

In appropriate cases the Council propose to accept, in lieu of formal training, work carried out in a staff appointment under the supervision of a Corporate Member. This will involve the submission of a certified statement detailing the character of the work and the range of basic experience it has afforded. If a part or the whole of the work cannot be accepted as training, it may be treated as 'additional experience' and as such will compensate for a deficiency in training on the basis that *two* years of 'additional experience' will compensate for *one* year's deficiency in training. In making their assessment the Council will take special note of any post-graduate course of an appropriate nature undertaken during this period.

For many years past the larger, and some comparatively small, firms of the electrical industry, and also the operating organizations, have devoted a great deal of care and much of their resources to the planning of training schemes for achieving the objectives to which I have referred, and have associated with the systematic movement of their graduates and student apprentices from department to department participation in lecture courses and discussions on the technical and organizational features of their concerns. These are not the only concerns, however, which need the services of men who have received a broad and thorough training. So far, the others have managed, when particular needs arose, by recruiting well-trained men from elsewhere. While in the interests of individual advancement no one should question the desirability of reasonable mobility from firm to firm, the scale on which movement has occurred during recent years has been highly inequitable and extremely wasteful. A more important consideration for the future, however, is the fact that the responsibility for training the increasingly large national pool of technologists—and, no less important, of technicians and craftsmen—required to accelerate the technical changes and achieve the enhanced productivity which are now possible cannot be carried by the few firms which have had the foresight to provide training facilities. Moreover, additional comprehensive training facilities must be made available as a matter of urgency on behalf of the increasing output of university graduates and if the Dip.Tech. scheme is to achieve the standards and objectives for which it was established. The shortage of these facilities has indeed become the Achilles' heel of our national plans for the further development of technological and technical education.

It would seem that this problem can be resolved only if the smaller and more specialized firms will collaborate in the organization of group schemes in which their limited individual resources are properly co-ordinated. A good example of such a scheme for the training of graduates and of student apprentices is the Scottish Electrical Training Scheme embracing five electrical manufacturing concerns and two Electricity Boards. Unfortunately there is not much evidence of initiative elsewhere to follow this example. It is a matter of speculation, therefore, as to how an extension of it is to be achieved, and, regrettably, of doubt as to whether it can ever be achieved on a sufficient scale in the absence of some form of financial incentive provided by the Government. The National Council for Technological Awards has appealed to the firms providing training for Dip.Tech. students to assist in ensuring that the content of the college and industrial parts of the sandwich courses are closely co-ordinated. But, as compared with the care it has taken in assessing the college facilities, their staffs, and the structure and curricula of the courses, and with its requirement for the appointment of external examiners, it has not yet been able to make a similar assessment of the nature and standards of the associated industrial training. This it is now approaching through the medium of a training panel, and no doubt the new Training Regulations of The Institution will be of assistance to it in this delicate and difficult matter.

It would be less than fair, and indeed incorrect, if having commented rather critically on certain aspects of technological education, I were to appear to profess that all is well with the training provided by the large electrical concerns to which I previously referred so favourably, but of which I know some of my late university colleagues to be in their turn far from uncritical. They remark that the training arrangements tend to be too inflexible to cater adequately for the more intelligent graduates; that too often the part spent in the workshops fails to avoid boredom and frustration; and that the opportunities afforded for the exercise of initiative and for the carrying of preliminary responsibility are too long delayed. These are very real problems. Their satisfactory resolution involves not only the provision of internal lecture courses and discussions on technical, organizational and economic aspects of the firms' activities, but also the planning of well-conceived projects to be carried out by individuals or groups under appropriate guidance and supervision. Though a good deal has been attempted in these directions in some cases, it cannot be questioned that there is considerable scope for further experimentation in pursuit of the aims to which I referred at the beginning of this Section. It is important to recognize, however, that this is a matter to which industrial training officers can make only a limited, though vital, contribution. They must receive the enthusiastic support and active help of men occupying positions of authority at all levels of their organizations, and particularly of those who are Corporate Members of The Institution. It has been a surprise and disappointment to me to observe how little some graduates are prepared to do to assist those who are seeking for information of which they themselves must have felt a similar need only a few years previously.

Even so there are limits to the help which should, or could in any case, be guaranteed. A real urge is stimulated, not inhibited, by difficulty, and discouraging circumstances will seldom fail to provide opportunity for those who are determined to find it. Those who complain most of the lack of opportunity

re usually those least capable of recognizing and accepting it. he taking of responsibility may be impeded, but, as evidenced y the careers of many of our predecessors, cannot be denied those who are determined to have it.

I am aware also that some senior members of industry, more articularly on the electronics side, are not persuaded as to the alue of organized schemes of graduate training, and consider hat all necessary experience can be obtained in a staff appointment. As already mentioned, this has been provided for within he new Training Regulations. I think it relevant to mention, owever, that the diploma in engineering of Continental countries seldom awarded on less than 5 years of college study from ge 18, and that its award usually requires up to 12 months of ndustrial 'training', of which, in some cases, 6 months must e obtained before entry upon the diploma course. It would eem to me a risky policy, therefore, to assume that a 3-year ourse of engineering science in this country affords by itself an quivalent preparation for responsible employment.

MANAGEMENT STUDIES

It is a big step from satisfying the examination requirements f one of the professional institutions to the attainment of enior executive positions on the research, development, design, nanufacturing, commercial or operating sides of engineering vork, for this involves much more than profitable participation n a scheme of training and in advanced courses such as I have nentioned. The ability to acquire knowledge is one thing—the bility to carry responsibility and exercise authority in relation this knowledge is quite another. The only effective means of stablishing that a man can carry responsibility is, of course, to ut him in a position where he is obliged to do so. In no other vay can he demonstrate the possession of certain essential ersonal qualities and abilities. When this has been demonstrated by success in one situation, it is a characteristic of good nanagement that he will be tested and matured in others of reater complexity, with the advice and example of his more enior colleagues to guide him.

Nevertheless, a great deal of thought has been given during ecent years to the question of what can be done outside the mmediate environment of employment to assist this process. s there a framework of general principles and a systematic ody of knowledge about industrial organization and management which, properly presented, will guide and assist young ngineers the better to assess their personal experiences in this eld? Can anything be done—in courses—to develop a man's bility to recognize and appreciate the significance to his own eld of work of the activities of others engaged in related fields; organize co-operative effort among men of whose respective pecialities he may have only limited detailed knowledge; to raw reliable deductions from, and make sound decisions on, nadequate evidence and in insufficient time; and to represent he views of other people, as well as to express his own, clearly nd concisely?

Much has been written on these, and other related, questions nd many post-graduate experiments are being tried within the niversities and technical colleges, and through the medium of aff courses organized by industrial concerns and public uthorities. The anxiety attaching to the former, particularly here the students lack outside experience, is lest they may ssume that successful participation in a course of study will utomatically endow them with the qualities essential to good nanagers. It is of the greatest importance that this danger hould be avoided.

THE UTILIZATION OF PROFESSIONAL ENGINEERS

So far, I have concentrated on the aims of engineering education and training and on some of the problems which are associated with the early stages of their achievement in circumstances where the student body and the facilities for accommodating and teaching it are expanding rapidly. The scale on which new facilities have been and are being provided has been governed by the abnormally high birth rate in the mid-1940's and by the need to correct the shortage of professional scientists and engineers to which frequent reference has been made during the past few years. A very important factor affecting our thinking on the latter point has been the comparison drawn between the output of similarly qualified scientists and engineers in this and other industrial countries. In his recent Rede Lecture in Cambridge, Sir Charles Snow[6] expresses the position as follows:

> Our population is small by the side of either the U.S.A. or the U.S.S.R. Roughly, if we compare like with like, and put scientists and engineers together, we are training at a professional level per head of the population one Englishman to every one and a half Americans to every two and a half Russians. Someone is wrong.

Taking this statement literally, it means that the U.S.A. is producing annually $4\frac{1}{2}$ times, and the U.S.S.R. 10 times, as many as we are.

Although these figures may paint rather too pessimistic a picture, and do not of course depict the relative starting-points in accumulated present numbers, they nevertheless give an indication of what is happening elsewhere. Of more direct relevance, however, are the results of an attempt by the Advisory Council on Scientific Policy in 1955–56 to quantify our own needs by an extensive inquiry among employers. These results were published in a White Paper entitled 'Scientific and Engineering Manpower in Great Britain', which recommended that the annual output of scientists and engineers of professional standard should be increased from the 1956 figure of around 10 000 to some 20 000 by the late 1960's. There seems no reason to doubt that this target will be met.

In my opinion we should have been culpable had we aimed at any lower figure. It is therefore with no intention of questioning it that I ask, Are we using the highly qualified persons we already possess to the best national advantage, and, if not, what steps should we take to correct the situation?

In an article in the March, 1959, *Journal* of The Institution entitled 'Recruitment of Professional Electrical Engineers', G. S. C. Lucas makes an analysis of the growth of our corporate membership during recent years and an attempt to project it into the late 1960's. In doing so, he suggests that in the course of their professional work some of our Corporate Members may be performing duties which, with appropriate replanning and with the fuller utilization of computing and other new techniques, might well be undertaken by men or women of lower academic qualifications than are required for corporate membership. This process of devolution is, of course, a continuous one in progressive industry, and it is characteristic that highly qualified people so relieved move into new fields of further creative effort with similar later consequences. Perhaps surprisingly at first sight, it is a process which increases rather than decreases the need for highly qualified people. But it demands for its progression the availability of people, themselves well educated and trained but to a different level, upon whom the work can be devolved. I believe in this connection that in stressing our shortage of scientists and technologists we have given inadequate recognition to the importance of the supporting contribution, and too little attention to the educational needs in the rapidly changing situation, of the much larger body of our technicians and craftsmen. Unfortunately, I cannot

develop here this aspect of our professional responsibility, but I have discussed it elsewhere,[7] and I would only add that I think it of great importance that we should help to devise a means of affording appropriate status to the high-grade electrical technicians on which we professional engineers are so dependent. Unfortunately, although a great deal of thought was given to this matter within The Institution a few years ago, no satisfactory solution was then forthcoming. I hope it may receive early reconsideration, since a solution would do much to allay the criticism which has been levelled at the new Examination Regulations.

There is a further aspect of our utilization of scientific and engineering manpower about which I find myself becoming increasingly concerned. It arises from the high degree of subdivision which characterizes our industrial structure. This subdivision produces among the larger organizations a considerable multiplication of research, development and design effort directed to the same, or substantially the same, technical objectives, and the possibility that no one of these concerns has the resources either of manpower or finance to launch a really major attack on a new field. Among the smaller ones it means all too often, not only an absence of research and development effort within themselves, but also, in varying degrees, an inability to take advantage of the results of work of this kind being done in the Research Associations on their behalf. Following my participation in a visit to Russia in 1955, I included in an article published in the Institution *Journal* the question, 'How can we develop a more effective co-ordination of our own national resources without loss of the benefits associated with a free society?' This question is in process of being answered, but not with us as participants, in the collaborative arrangements now being made on the Continent as part of the European Free Trade Area negotiations. Agreements for joint research and development programmes, and for the co-ordination of other activities, are being worked out between groups of previously competing firms in different countries, and we may soon be faced with a very serious situation in the export field. These countries are no shorter of scientists and technologists than we are, if indeed they are as short. It therefore behoves the senior members of professions like our own to do all they can to ensure in their respective fields that what strength we have is not misapplied in unnecessary duplication, to the possible frustration of the young men who are joining us in our professional enterprises, and the detriment of our national wellbeing.

OUR RESPONSIBILITIES OVERSEAS, PARTICULARLY TO THE COMMONWEALTH

In the early part of my address I said that our scientists and technologists have become not only the guardians and guarantors of our national economy, but also the agents of a new diplomacy in which more than an expanding export trade is at stake. This something more is the improvement, undertaken for its own sake and not merely as an act of self-interest (though in fact this interest would be safeguarded automatically), of the distressingly poor economic and social conditions of vast portions of the world community.

In his Presidential Address entitled 'Technology and World Advancement' to the British Association for the Advancement of Science in 1957, Professor P. M. S. Blackett[8] said,

> In addition to maintaining its existing wealth, the Western world is saving and investing productively some 10 per cent of its average income of £300 per head (at 1949 prices); that is some £30 a year per head is being invested in additional plant and machinery to create more wealth. The pre-industrial countries of Asia only have about £20 a year per head to live on, that is for both consumption and production goods.

Professor Blackett's advocacy was for large-scale capital assistance to enable these underdeveloped countries to 'achieve the take-off towards sustained economic growth'. Mine will be for more educational assistance to the same end.

In fact the assistance which this country has already given within the Commonwealth since the war has been considerable—much more perhaps than is generally realized or for which we are always given due credit overseas. Thus the Colonial Office has provided through the Inter-University Council for Higher Education Overseas more than £12 million for university and university college development in Ghana, Hong Kong, Malaya, Malta, Nigeria, Rhodesia and Nyasaland, Uganda and the West Indies; and through the Council for Overseas Colleges of Arts, Science and Technology some £3 million for the establishment of these colleges in East Africa, Ghana, Nigeria, Sierra Leone, Singapore and the West Indies. In addition, the Commonwealth Relations Office has contributed to the Colombo Plan for assistance to South and South-East Asian countries close to £4 million for the provision of educational and research equipment, of expert advisers and of training grants. Members of The Institution will already be aware through an article published in the March, 1959, issue of the *Journal* of the latest offer of help under the auspices of the Plan, that of joint sponsorship by the Commonwealth Relations Office and the Federation of British Industries of a College of Engineering and Technology in the University of New Delhi.

In aggregate these contributions to the furtherance of education in the underdeveloped countries are second in amount only to those of the United States. On the other hand, Russia and West Germany have begun to play a more substantial part, and their sponsorship, for example, of the Institutes of Technology at Bombay and Madras, respectively, is on a particularly generous scale as regards both equipment and staff. Staffing is of crucial importance, and I am not a little anxious, for both absolute and comparative reasons, about this aspect of our undertaking in New Delhi.

However, the problem is a more general one, for it has proved, not only extremely difficult to staff from this country the institutions for which we have carried an initiating responsibility, but impossible to fill more than a fraction of the teaching posts overseas for which our help has been specifically sought. These difficulties have undoubtedly arisen from the shortage of teachers to meet the needs of our own educational developments. But I feel that they are also due in part to the lack of a clearly defined and unified plan for the secondment of teachers overseas as an act of national policy, carrying with it appropriate safeguards for their return, and an appeal to teachers—and not least to teachers of engineering—to devote a few years of their lives to this kind of international service. They would incidentally make a profound contribution to the future well-being of their own country.

There is a further way in which we have given great assistance, but in which we must also increase our contribution. We have good reason to be proud and thankful that so many of those now occupying senior positions in all walks of life within the Commonwealth and Colonies, and indeed in many other countries, came here as young men for their education and training. They have been coming during recent years in ever increasing numbers, under the auspices of the British Council and the Colombo Plan, of the Athlone Fellowship and the F.B.I. Overseas Scholarship Schemes, of their own Governments, and by individual initiative. This flow is now to be augmented by the large number of scholarships tenable in this country which the British Government offered at the Commonwealth Conference held in Oxford in July.

At the present time there are upwards of 40 000 overseas

tudents, including some 26 000 from the Commonwealth, in his country. Of the latter over 7 000 are university students, nd of these about 1 600 are following undergraduate courses n technological subjects. No doubt a substantial proportion of he 2 600 post-graduate university students are also technologists. further 6 500 from the Commonwealth are studying in the echnical colleges.

In respect of their formal education we need, I think, have o anxieties about these young people. On the whole they nake good and successful students and they exercise a valuble educational influence on our own. Moreover many, nainly voluntary, organizations are performing a supplementary, nore informal but no less important, educational and social ervice on their behalf. But we in engineering are faced with the erious problem that it is becoming increasingly difficult to make rrangements in industry and the operating organizations for heir practical training. This means that they are unable to btain here what their own countries are least able to provide in he present early stages of industrial development and that on heir return home they will be the less competent to contribute to t. Many of them are reluctantly taking advantage of opporunities being offered on the Continent, and they may well feel he more dissatisfied if the training which these opportunities fford is considered by the Institutions to be inadequate.

The difficulty in obtaining training facilities also applies to he more mature persons whom the Commonwealth Relations Office, the Colonial Office and the British Council wish to bring ere to refurbish their professional skills and to learn the latest echniques.

I have already discussed the basic reason for this difficulty. ts solution is to be found, if it can be found, only in the accepance by the smaller and more specialist firms of a greater neasure of responsibility for providing good training facilities, ither within themselves individually or by collaborative effort. n fact these firms have special merits for overseas students in hat they compare more closely than do the large organizations vith the type of manufacturing concern of which the industry of heir countries is likely to be composed. It would be invaluable or these men to have the opportunity of training under proper uidance within a group of small firms, each with its characeristic production techniques, organizational structure and dministrative methods, and of making comparisons between hem in these respects.

Finally, there is one category of overseas visitor to which I ttach special importance, that of members of staff of the ngineering departments of the Commonwealth and Colonial iniversities and colleges. We must do all we can to help these nen to establish high standards of professional competence and onduct in their own countries, and I hope therefore that ndustry will make a special effort on their behalf. I trust it vill also be possible to accommodate increasing numbers of hem in the technical teacher training colleges now undergoing xpansion.

THE UNITY OF THE ENGINEERING PROFESSION

In most of the preceding I have referred to engineering in the eneral sense, because much that I have tried to say applies to ach of its constituent branches. I now want to refer to two ppositely directed trends within its professional organization. One arises from an increasing recognition of the growing interlependence of these branches, and is directed towards closer ollaboration between existing professional bodies and the voidance, by this collaboration, of the creation of new ones. This has found expression in the joint committees of the Institutions of Civil, Mechanical and Electrical Engineers; in the establishment by these Institutions, The Institution of Chemical Engineers and the Institute of Physics of the British Nuclear Energy Conference and the subsequent incorporation of several other bodies as joint sponsors of it; and in the creation by some 40 institutes, institutions and societies of the British Conference on Automation and Computation. The recently announced proposal for amalgamation of the Institute of Physics and the Physical Society is a closely related step in the same direction.

The other trend arises from the desire of representatives of new fields of technical activity to secure distinctive recognition and status for them.

It is of great importance that the first of these trends should progress as rapidly as possible so that professional engineers may acquire a fuller sense of corporate responsibility in professional and public affairs, and achieve a collective status in the public mind more in accord with the importance of their national service. But its progress will be impeded if the initiative and vitality which characterize those associated with new developments are not given early, enthusiastic and satisfying recognition and support. Our own Institution is endeavouring to fulfil this responsibility towards its vigorous and rapidly expanding Electronics and Communications Section. The name of this Section was changed recently so as to lay emphasis on the growing importance of electronics within electrical engineering. This was expressive of The Institution's determination to afford full representation to those engaged in this branch of the electrical profession and to cater comprehensively for them. Consideration is now being given to further steps which may assist in these directions.

Anything which can be done towards unifying the profession at home while at the same time ensuring the full vitality of its constituent parts is of value in assisting our professional colleagues overseas. It is particularly important that our three major Institutions should hold analogous views on matters of education, training and professional recognition, since their joint representations to the Commonwealth Engineering Conference and at meetings of Eusec are of major significance to the progress of these international bodies.

THE ENGINEER—HIS DUE AND HIS DUTY IN LIFE

In my Introduction I referred to the responsibility which we senior members carry for ensuring that the newcomers to our profession are properly prepared by education, training, and example, for participation in its work. I did not intend the word *example* to apply only to our scientific, technological and administrative activities as professional engineers. My use of it was in fact a reflection of the inspiration which I derived from a paper read before the North-Western Centre of The Institution in 1925, the year of my graduation at Manchester University. This paper was entitled 'The Engineer—his Due and his Duty in Life', by Thomas Carter, Member,[9] and the recollection of its presentation and of the discussion which followed has remained with me over the intervening years. That evening I felt proud to be entering the electrical engineering profession. I have decided that I cannot conclude my address better than by quoting from the opening Section of this paper, which the late Mr. Carter headed 'The Rights and the Duties of Life' and which reads as follows:

> In these days, when many standards of the past are disappearing, when new thoughts are being conceived and new views are struggling for recognition, and when more than ever the safety of the future depends on the well-directed efforts of men of wide vision and clear understanding, it is not too much to say that unless each of us is contriving somehow to increase the common good, he were much better dead. . . .
>
> We are born into a family, into a nation, into the world; we

inherit from all the past; we are played upon by things around us, and we react on them in our turn; each one of us has his own qualities, his own defects, his own potential contribution to the service of his fellows . . . There are, then, two sides to a man's life, together making it complete: the one, his right to live; the other, his duty to the community . . . His right is to expect to be prepared in his youth for a job that he can do in his working days with enough comfort to leave his spirit unquenched if he grows to be old . . . On the other hand, the more we give every man a chance to reach his best, the more must he recognize that this good comes to him from the community, and the more must he strive while following his own bent, to avoid every activity that will put a brake on the wheels of progress. This, then, is a proper life: a constant giving and receiving, a perpetual interchange of services, ideas, and commodities, with an unfailing consideration of our neighbour's good as well as of our own, and a constant recollection that those who forget their common obligations, and merely demand their own due without caring what happens to others, are the slayers of the nation's soul. There is no right without its corresponding duty.

I hope this quotation may move many members of The Institution, the younger ones particularly, to read the paper and the ensuing discussion in full, and that it will help them, as it has helped me, to see more clearly their duties to the engineering profession and to the wider community of people, and of peoples, of which it forms a part.

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PAPER AND MONOGRAPH PUBLISHED INDIVIDUALLY

Summaries are given below of a paper and a monograph which have been published individually. The paper is free of charge; the price of the monograph is 2s. (post free). Applications, quoting the serial numbers as well as the authors' names, and accompanied by a remittance where appropriate, should be addressed to the Secretary. For convenience, books of five vouchers, price 10s., can be supplied.

The Logmotor—a Cylindrical Brushless Variable-Speed Induction Motor. Paper No. 3149 U.

Prof. F. C. Williams, O.B.E., D.Sc., D.Phil., F.R.S., E. R. Laithwaite, M.Sc., Ph.D., J. F. Eastham, M.Sc., and L. S. Piggott, M.Sc.

In a conventional induction motor the synchronous speed at the rotor surface is set by the phase difference between currents in adjacent slots and the spacing of the slots. The synchronous speed may be increased by changing the phase of the current in each slot progressively so as effectively to stretch the poles. The paper describes a transformer arrangement giving a multi-phase output, which can provide such a 'phase-stretching' system to be used to supply the stator of a squirrel-cage induction motor. The transformer is similar to a conventional phase-shifting transformer, except that the pitch of each coil of the primary is proportional to the log of its distance from a fixed point in the system. The primary and secondary of the transformer are analogous to the C and D scales of a slide rule, and movement of the primary relative to the secondary in a variation of the phase increment between adjacent secondary coils. The secondary is connected to the stator winding of the motor in such a way as to provide a uniform-velocity field in the latter, the velocity being varied by adjusting the position of the primary of the transformer. The method of construction of an experimental machine is described and test results over a speed range of 4:1 are included.

The paper will be read at a London meeting during the 1960–61 Session.

Life Expectancy of Electrical Machines with Variable Loads. Monograph No. 354 U.

Joseph Ben Uri, Dr.Ing.

Modern economics demand a reduction in costs and prices, and this usually means reduction in the amount of materials used. The danger is that some of the insulation materials in use have a cellulose base, which means that their ageing may be endangered if the temperature is higher than the 110° C, since, above this temperature, the cellulose materials tend to change quickly their consistency and mechanical strength.

It has been generally agreed that the life expectancy of electrical machines should be seven years when continuously under rated load. General equations for change in life expectancy with temperature have been experimentally and partly deductively found and presented by Montsinger and Bussing, and experiments show that the equations are correct for continuous loads. But when the load changes the heating and cooling periods must be taken into consideration. Short-circuits or heavy overloads can be very dangerous.

Equations have been developed for load changes and for straight-line and exponential temperature changes, and it is shown that the cooling-off period especially can be very dangerous and take a very appreciable part of the life expectancy of the electrical equipment in question. Sample calculations on transformer and intermittent motor loads are included.

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Paper No. 3209
Feb. 1960
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SUPPLY SECTION: CHAIRMAN'S ADDRESS

By J. R. MORTLOCK, B.Sc.(Eng.), Ph.D., Member.

'WHITHER NEXT?'

(*Address delivered* 21*st October*, 1959.)

Materialistically, electrical energy consumption is a good ieasure of progress to a higher standard of living. In indus-ialized countries it is usual to assume a rate of growth which oubles consumption about every ten years. There are many ther countries where this approximate law applies but the *per ıpita* consumption is too low. A doubling in 5 years is ssential if, in comparison with their more fortunate neighbours, iey are to progress adequately. For example, if the present onsumptions are in the ratio of 4 : 1 and the rates of growth re maintained, it would take 20 years for the consumptions to e the same. Why have they lagged? Perhaps Nature ensured 1 ample, if monotonous, food supply, climatically there was ttle need for clothing, and housing could be rudimentary—in fect the bare essentials of living were easy and available to all or little effort, and apart from ornamentation there was little ompetition. Again, life might have been so hard that there as little time for other than the essentials. Perhaps their basic hilosophy was such that materialism was eschewed and manual ıbour considered definitely non-U.

Using the term 'civilization' generally, there have been periods hen China, India, Greece, Italy, etc., led the way, but in turn iey lost their drive and were superseded. Contrary to popular elief, Toynbee states that out of 21 civilizations identified 19 ollapsed internally and only two due to invasion. The detailed asons are for historians to argue, but in general they were nbalanced with a small leisured class and a large mass living at low level. With the advent of the control of power and the creasing availability of energy, man-power, bullock-power or orse-power ceased to be a basic unit and an opportunity for the dvancement of the artisan was created. To differing degrees iis opportunity was accepted by different nations, and Great ritain emerged as the primary power; later the United States; nd now, with a forced acceleration, Russia is advancing rapidly. evertheless the greater part of the world's population still lives an extremely low level and the raising of this level is a duty hich has been appreciated only recently. However it is done, paramount requirement is the availability of energy in an easily onvertible form. This requires a widespread electrical network.

In highly industralized countries the *per capita* electrical con-ımption does not show any signs of saturation, and if to this rowth is added the desired increase in consumption in the nder-developed countries, the demand for electrical products ıould continue to increase materially. Our problem, and also at of some European countries, is at the least to retain, but referably to increase, our share of this market. Obviously if e under-developed countries are to industralize they must anufacture, and consequently there could be a gradual reduc-on in the market for those articles which are made easily. I y 'could' advisedly, as advances in design and manufacturing chniques would often make the imported article preferable or place it with one cheaper and, or, better. These advances ust be continuous, and complacency—often called conservatism —must be eschewed; otherwise we will be led instead of leading. The older generation dictate policy, the next generation implement it and develop techniques, but the future lies largely in the hands of the young generation and, through them, with the universities and technical colleges. Progress is due basically to the work of scientists and engineers, and unless their quality, and to a lesser degree their quantity, advances a nation will suffer.

Let us consider some of the advances in electrical engineering. Amongst many, two of the most striking are the application of nuclear fission to peaceful uses, and in the field of semiconductors. The former is the more spectacular, and its use for power generation has been well publicized, but it should be remembered that it is still an alternative source, albeit very attractive for some applications. To humanity in general a by-product, radioactive isotopes are of more fundamental use. Sensing devices, strangely just streamlined versions of those used 25 to 50 years ago, enable radioactive chemicals to be followed through the body. Medical science has benefited accordingly. The degree to which carbon-14 is present enables the archaeologist to be more precise regarding the age of artefacts. Cobalt-60 can be used to determine the consistency of steel up to several inches thick, and in its container is more robust than the conventional X-ray equipment and therefore more suitable for factory and site work. Irradiation of cereals results in negligible loss from insects, and as this loss is between 10% and 40%, it can help materially in food conservation—a world problem. The diversity of, and interrelationship between, interests arises out of the combined efforts of scientists, mathematicians and engineers. Often buried in the detail of our individual work, we do not realize that we are part of a community with very diverse interests.

The relative destructive power of bombs based on 'fusion' and 'fission' has opened—at present only just—the door to a new field, the direct conversion of atomic energy to electrical. The present implication is that the output could be direct current, and if so there will have to be some reorientation in heavy engineering.

The use of semiconductors as rather inefficient and temperamental rectifiers is familiar to many of the older generation, who, in the early days of radio, tried to manipulate a cat's-whisker. In its modern version it can handle some thousands of kilowatts with high efficiency and lack of temperament. In 1948 the transistor principle was discovered, and its subsequent development has enabled a semiconductor to behave essentially as the more conventional thermionic valve. Nowadays single wafers of germanium or silicon can handle up to 100 watts when used as amplifiers and up to 5 kW when used as switching devices. All this in a little over 11 years. The future? If the rate of progress is maintained, mercury-arc rectifiers will be confined to the science museum, but will it be maintained? Transistor techniques continue to develop and even now permit very material reductions in the size of complex control equipment. In the power system field they will find an increasing application in protective gear, provided that the development is based on

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the basic fundamentals and limitations of transistors rather than being a substitution for existing equipment.

In the transmission field only a few years ago 400 kV was considered as the upper limit, but now 600 kV is acceptable and is being considered for projects in the U.S.S.R. and Canada. What has led to this advance? Mainly a better appreciation of the physical phenomena associated with the interruption of current. From the random over-voltages produced by uncontrolled interrupters we have now reached a stage where an over-voltage factor of 2·3 can be guaranteed for new designs. Such advances have enabled the U.S.S.R. and Sweden to reassess their existing 400 kV transmission systems and to propose using them at 500 kV when the load justifies the change. Circuit-breakers with an interrupting rating of 25 000 MVA at 600 kV have been offered, and 50 000 MVA is possible.

To Sweden must be given the credit for pioneering the application of series capacitors at 400 kV. Their success has enabled us to increase materially the power which can be transmitted over long distances.

A pertinent query is, How about direct current in the e.h.v. field? The largest scheme being constructed is in the U.S.S.R. and it is rated at ±400 kV, 750 MW. It will connect, mainly through a 300-mile overhead line, Stalingrad with the Donbas and is basically an asynchronous tie. The U.S.S.R. engineers admit it is experimental and intended as a guide to the possible transmission of 2 000–3 000 MW 1 000 miles or more from hydro-electric sources in Siberia to the Urals. Like other d.c. schemes it uses mercury-arc rectifiers and inverters, but will future schemes use these devices or will some development in the semiconductor field out-date them? At present the difficulties appear great and the prospects poor, but we have progressed far in 11 years.

In a different field, perfect whiskers of iron, free from atomic imperfections, have been produced in laboratories and shown to have strengths of 2 000 000 lb/in^2. This compares with our best steels with strengths 1/20 of this value. Will these interesting laboratory phenomena result in a material improvement in the strengths of metals in our time? More widely, will they result in advances in our fundamental knowledge with applications in many fields?

Electronics in its applications continues to increase rapidly and must do so. A U.S.A. forecast is that in 10 years' time there should be 50% more goods and services available if the level of living is to continue to rise steadily. This will have to be obtained with an increase in the labour force of not more than 10%. It follows that productivity will have to increase by about 3% per year, and to attain this automation will have to increase. Electronics, in some form, enters into the primary control of practically all automatic devices, and therefore there should be a steady increase in its applications. An engineer in this field has to be conversant not only with electronic circuitry but with the details of the process being controlled. A good fundamental background in physics, engineering and mathematics is essential.

Mathematics has been and, unfortunately, still is the *bête noire* of most engineers. A possible reason is that it is the most rigorous and logical of mental disciplines, and, human nature being what it is, therefore has no popular appeal. However, I believe there is a deeper reason. Likes and dislikes of subjects are often engendered at an early age, and a teacher of mathematics can foster an interest or destroy it. The majority of engineers will admit that pure mathematics can be a dry subject, whereas applied mathematics, dealing with earthy engineering, is the more interesting. From personal experience at college, our pure mathematics lecturer made the subject alive and interesting and it was popular with both electrical and mechanical students, whereas the applied mathematics lecturer, much bette qualified, succeeded in making the more interesting subjec unpopular.

Empiricism is based usually on a lack of detailed knowledg of basic physics plus, often, inadequate familiarity with mathematics. Any design is amenable to some degree of calculation but the accuracy of the result will be dependent on the simplifyin assumptions made. Often through familiarity these assumption are forgotten, and even I have been guilty. The first time ou transient analyser was used for the assessment of restrikin voltages, the source was earthed and the 3-phase fault unearthed The recovery voltage obtained was, say, V. The fault was the earthed, but the expected result of $V/1{\cdot}5$ was not obtained. A complete check of the circuitry and technique showed nothin untoward, and the same results were obtained on a repeat test Consideration of an equivalent circuit, Fig. 1(a), immediatel showed the correctness of the transient analyser result and th dependence of the recovery voltage on the system earthing conditions, Fig. 1(b). The 1·5 factor applies only for a specific condition which happens to be common in test plants. A salutary lesson.

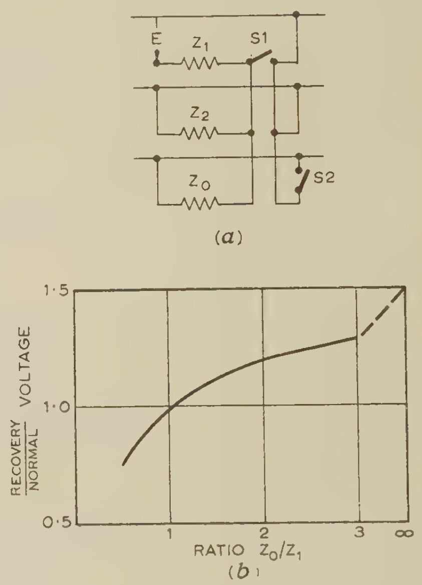

Fig. 1.—Effect of earthing conditions on recovery voltages.

(a) Equivalent symmetrical-component circuit.
S_1 closed = 3-phase fault.
S_2 closed = Fault earthed.
S_1 open = 1-phase open-circuit.
= First phase to clear on a 3-phase fault.
S_2 open = Fault clear of earth.

(b) Effect of zero-sequence impedance on recovery voltage.
$Z_1 = Z_2$

This example illustrates one of the fundamental differences between simulators (models) and digital computers. With the former the basis is physics and the mathematics takes care of itself, provided that the correct driving function is applied and the circuitry is valid. With the latter, although the mathematics may be simple, the programme must be logical and complete. Often this is not possible owing to the lack of knowledge of some phenomenon in sufficient detail. For general investigational work the simulator is preferable, but for specific work, when the interrelations between the various parameters are known, the digital is preferable. An incidental advantage of the latter is best illustrated by an example. An initial very high rate of rise of restriking voltage but of limited voltage magnitude can be obtained on an overhead-line system with a fault a short distance away from a circuit-breaker. This is

cause the line behaves essentially as a resistor for a short time. easonable accuracy would require the short line between the ult and the circuit-breaker to be represented by about 5 elements. This would fix the scaling factor on a transient alyser and could make the representation of other elements fficult; on a computer it would present no difficulty.

Analogue devices have many of the characteristics of simu- tors but have a major advantage over both simulators and gital computers in that they can work in real time. Conse- ently it is possible to incorporate into the circuitry of the alogue parts of the actual control being investigated.

What of the future? The use of digital computers will extend to new fields only when we are able to state, unequivocally, e logical steps in the solutions of problems. These steps will derived from studies of the results obtained on the actual paratus or systems and from simulator and analogue devices. effect there will be considerable pressure exerted to advance nthesis, particularly in those fields of basic science which are ell understood. This must reflect on the training of young gineers. In my day about 90% of experiments in college boratories were usually done with machines designed for a ecific purpose and little was done in the way of synthesis. the immediate future the ratio should be reversed and experi- entation confined to special tests to check theoretical models. o this end the young engineer should have sufficient familiarity th digital computers to use them readily for the detail work it must have sufficient mathematical background to be able enunciate clearly the problem.

Against this might be cited the difficulties arising from the sic techniques and philosophies differing from computer to mputer. At present this can be met by the specialist pro- amming staff associated with any computer, and in the future is possible that a special international language will be avail- ble. Even now, by taking about twice as long to obtain a lution, it is possible to train an engineer in about a day to e a particular type of computer. He can instruct it to cal- late, for example, $\sin x$ without giving instructions on proce- ire, as this is stored in the computer in advance. On receiving e instruction it will search in its memory store, locate the ocedural instructions and calculate $\sin x$ accordingly. An perienced programmer would save the time taken by the mputer to search through its store, as he (or more usually she) ould incorporate the procedure in his instructions. But this detail, as the important factor is the basic logical approach to e problem and this would not vary. Lady Lovelace's com- ent in 1842, 'The computer can do whatever we know how to der it to perform', still applies. Original thinking is the erogative of the human mind, and while a computer can be of aterial help it can exercise judgment only in accordance with s instructions. In my experience the development of design ogrammes for even well-established apparatus has shown the cessity for some fundamental thinking and reassessment of cepted theories.

With this relatively new tool the initial tendency is to use it sentially as a substitute for a slide-rule. This soon gives way a synthesis approach and ultimately optimization. The latter best illustrated by an example. Suppose that for a specific ece of apparatus there were 10 discrete values for each of four riables (flux density, etc.); then the number of possible designs $10^4 = 10\,000$. Obviously the designer would exercise his dgment and instruct the computer to ignore certain combina- ons, but still there could be 1 000 designs to consider. The mputer could be instructed to work through these designs and lect that one which had the minimum weight or minimum ctory cost or minimum annual charge to a supply undertaking.

The technique of linear programming is extending into the electrical distribution field, but this application is still in its infancy. One of the difficulties is the large amount of storage required in a computer memory. Perhaps a simple example from another field will illustrate better what is meant by 'linear programming'. A caterer has certain commitments for a particular week which require the use of 1 000 serviettes. He has available 500 clean ones at the start of the week and can get them laundered in 24 hours at a cost of x each, or in 48 hours at a smaller cost, y each. He can buy new ones at a cost of z each. Linear programming would enable him to determine how many new ones he should buy and how many should be laundered at x and y rates so as to give him the minimum overall cost. The technique has been used in assessing the maximum hydro-electric power production in the Missouri Valley associated with adequate flood control and irrigation and allowing for seasonal variations in rainfall, topography, etc. It seems reasonable to assume that in the future effective hydro-electric potential will have to be assessed on this basis rather than just water availability.

It is difficult to keep abreast of technical progress, as it is estimated that 13 million pages of technical literature are produced each year. Even in a narrow field the verbiage is colossal, and, apart from keeping up to date, somewhere amongst it might be the solution to a particularly refractory problem. The difficulty is twofold: first the lack of time adequately to digest the literature, and secondly the possession of a perfect memory. Possibly in the future this can be met by using variants of computers in which the information can be stored and cross-indexed so that bibliographies on any particular aspect can be provided on demand in a very short time.

With the analytical facilities now available a better appreciation of the overall performance of a group of equipment can be obtained. In some instances this is essential and in others the benefit to be derived is very material. For example, with a small induction motor the local busbar can be considered as an infinite source and its performance assessed as an isolated unit. With a large motor it might be necessary to assess the performance as part of a system including the transmission network and source and to design it to suit the overall circuit and its specific duty. Again, the performance of an automatic voltage regulator with a given machine can be assessed and advantage taken of the increased stability at leading power factor which can be obtained. Soon it should be possible to assess the overall static and transient performance of boiler, governor, turbine, generator and voltage regulator when operating under different network conditions. This is very desirable when the machine is rated at 500 MW and the station possibly at 2 000 MW. Equally in the hydro-electric field, machines of 300–400 MW are on offer and stations of 3 000 MW are being considered.

In some countries where electricity has to be competitive with other forms of energy it is essential that the system should be run at all times at minimum cost. A group of power stations, with an aggregate capacity of about 1 500 MW, is now being controlled by a computer to this end. It is admitted that the scheme is complex and costly, but economically it has been fully justified.

Time does not permit our wandering into other technical fields, but it is not necessary, as the salient feature of an accelerating expansion in the boundaries of scientific knowledge is self-evident. Herein lies a risk in that, for the specialist in particular, there is great temptation to concentrate in his chosen narrow field to the exclusion of interest in unrelated subjects, more specifically the 'humanities'. This aspect of engineering life is being appreciated increasingly by the universities. It is hoped that more stress will be placed on it by them, and still

more so by the colleges of advanced technology, as they lack that broadening which can be obtained in a university by the intermingling of the various faculties. Whether history, economics, etc., should be subjects in an engineering curriculum has yet to be agreed. The world has progressed and will continue to progress materialistically due to the continued advances in scientific knowledge and its applications, but has it progressed equally in the 'humanities'? Is it not desirable that the 'humanities' should consider, possibly, physics as part of their curriculum? At the least it would engender mutual respect and tend to destroy the unrealistic superiority assumed by them.

This engineering education problem is very pertinent with the present expansion in training facilities the primary purpose of which is to increase the proportion of the population employed in these fields. This can be only a short-term policy, as a continued increase could result in an unbalance in general employment to the detriment of the community. It follows that the effort available should be used more and more effectively, and equally that recruitment should be of the highest quality. The professional engineer should be encouraged to use those aids which relieve him of tedious calculations and to assign the more routine work to technicians. His higher education has been aimed at making him think, and he should have freedom to do so; thereby his effectiveness will be increased.

Of the factors which could lead to the required quality in recruitment the most obvious is the financial one. In trying to assess the value of this 'carrot' in relation to other employment, the distribution of income, salary, etc., for a number of countries was examined and it was found that they conformed generally to a similar pattern. This is shown for Great Britain for the last financial year in Fig. 2. A relative value scale is used to make comparisons easier, as the factor of interest is the relative distribution. For other countries, with the same political tenets, the distribution characteristics lie slightly above and below. For Great Britain it was not possible to obtain sufficient data to show similarly the distribution of professional incomes, salaries, etc., but such information was available for one of the Commonwealth countries and is shown also in Fig. 2. It is reasonable to consider it as typical. If the relative value scale were replaced by one of actual values, this characteristic would cut that for Great Britain—an average—at about 1/10 of the population. The conclusions are (*a*) that there is some attraction in higher earnings in the earlier stages of a professional career, and (*b*) that there is greater financial attraction in non-professional work in the later stages. In contradistinction, with a materialistic political philosophy, as in the U.S.S.R., it is the professional man, particularly the scientist and engineer, who is paramount.

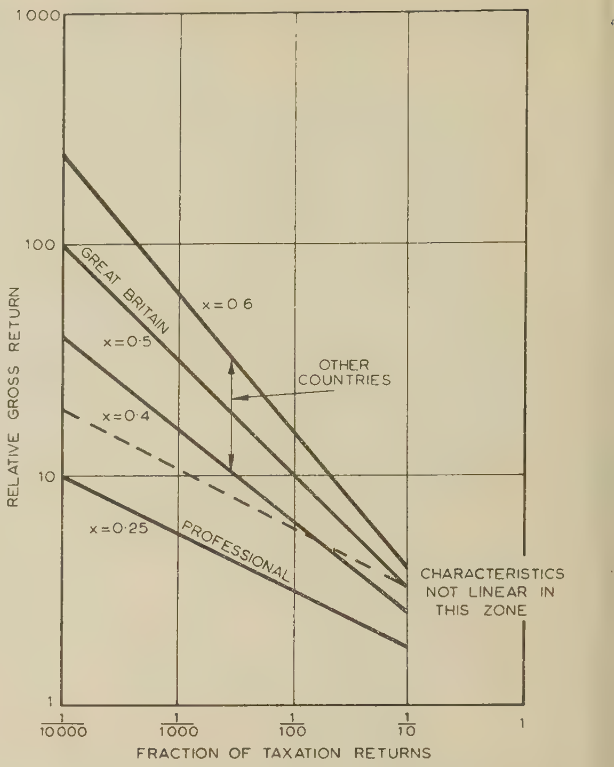

Fig. 2.—Relation between relative gross value of taxation returns and fraction of such returns.

Return × (Population fraction)^x = 1

Are the remuneration structures and political philosophies correlated? I do not know, but if the possibility is assumed, do we want to follow the materialistic pattern or are we content with our way of life? If the latter, it would appear that, provided the basic standard is adequate and the disparity with the rest of the community not too great, financial attractions are not paramount in attracting the best recruitment. The appeal must be to something deeper, and in conclusion I cannot do better than quote Faraday:

> The mental education afforded by science is rendered super-eminent in dignity, in practical application and utility; for, by enabling the mind to apply natural power through law, it conveys the gifts of God to man.

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Feb. 1960

UTILIZATION SECTION: CHAIRMAN'S ADDRESS

By T. E. HOUGHTON, M.Eng., M.I.C.E., M.I.Mech.E., Member.

'THE ELECTRICAL ENGINEER AND THE HEAVY CHEMICAL INDUSTRY'

(ABSTRACT *of Address delivered* 15*th October*, 1959.)

Chemical manufacturers were among the first to appreciate e value of electricity as a service to their factories, and at the rn of the century it was becoming fairly widely used in many emical works. At the outset, it was used for motive power d lighting, but with the development of electrochemical and ectrothermal processes it became an essential service in many anches of the chemical industry and large supplies are now quired for these purposes. There are no records of the annual nsumption of electricity by the industry 60 years ago, but om such information as is available I estimate this was of the der of 50 million kWh in 1900. To-day the figure exceeds 000 million kWh and is still increasing quite rapidly.

Before the Second World War, some three-quarters of the ectricity required was privately generated, but the proportion l to about one-third during the war years, chiefly because the rchase of plant was difficult under the prevailing conditions. ivate generation now accounts for about 31% of the total wer required, but is increasing due principally to the installa-on of several fairly large combined process-steam-electric ations working at high or even very high steam pressures d temperatures, with a consequent increase in energy generated r unit of process steam and also, to some extent, to the ovision of additional condensing generating plant.

Choice of Supply

In the early days, public supplies of electricity were rarely ailable in the centres of the chemical industry and manu-cturers had, perforce, to generate their own supplies in most ses. This, however, had much in its favour, as many works ere able to combine the generation of electricity with the supply exhaust steam to processes, a practice which was economic spite the low cost of coal then ruling.

Nowadays, in most industries, the choice of supply is no nger a problem, for abundant and reliable supplies of electricity e generally available from the public system. In the heavy emical industry, however, and particularly in those branches orking electrochemical or similar high-load-factor processes, e problem is not so simple, for the cost of power is usually a rge fraction of the total cost of the product and it is essen-l, in consequence, to obtain supplies at the lowest possible st commensurate with high reliability and economic capital penditure.

The case for private generation should therefore always be haustively investigated, and if, at the same time, supplies of ocess steam at medium or low pressure are also required, it nerally pays to build a private generating station based on the e of some form of back-pressure or pass-out turbo-alternator, as to enable full economic use, from all points of view, to be ade of the installation.

It should be borne in mind that, if a relatively large combined at-electric station is to be erected, the extra cost of installing ndensing turbo-alternators for load-balancing purposes or en for supplying the remainder of the load is largely marginal because all the essential services, such as coal- and ash-handling plant, water supply, railways, workshops, amenities, etc., and the operating and maintenance staffs have to be provided in any event.

There are a number of well-known stations of this type, the most recent being the Thornton power station of Imperial Chemical Industries, which was commissioned a short time ago. The steam conditions at this station, which has an installed capacity of 39 MW in one line of turbo-alternators, are 1 600 lb/in^2 and 1 060° F. The three boilers are of the cyclone-fired type, and the 24 MW primary turbine exhausts at 200 lb/in^2 to the process steam mains and to a 15 MW feed-heating and condensing turbine, the final feed temperature being 425° F. Electricity and steam are supplied to four neighbouring works, and this has enabled four groups of old low-pressure boilers to be shut down, with an estimated annual coal saving of 90 000 tons.

The only condensate available is that from the feed-heating set, and the feed-water make-up is, in consequence, of the order of 80%. The raw water for this make-up is treated in a mixed-bed demineralizing plant, from which water of a satisfactory quality is obtained.

The station is interconnected with the 132 kV Grid via the Company's private 33 kV system.

Only rarely does it happen that the electrical load and the process steam demand are balanced, so that simple back-pressure or pass-out back-pressure turbines can be used and condensing sets are not required. Under these circumstances the manufacturer can generate all the electricity he wants at an efficiency which may exceed 80%, and his process steam at an efficiency of 86%–88%, with a combined efficiency between the upper and lower limits.

It has always seemed to me a great pity that there is not more collaboration between manufacturers requiring supplies of process steam as well as electricity and the public supply authorities in the provision of the combined supply of heat and power from a public station where the conditions are favourable, for I am certain that in many cases such an arrangement would be to the advantage of both parties and of the national economy. One of the obstacles to this appears to be a reluctance to deal with large quantities of treated make-up water, but this is not a realistic objection, for a number of high-pressure stations are working quite satisfactorily under these conditions.

Converting and Rectifying Plant for Electrolytic Service

Electrolytic processes usually require large and reliable supplies of direct current at high load factors, and the electrical machinery to provide them has to work continuously 24 hours a day for as long as possible, service periods of 8 200–8 500 hours per annum being quite usual even for rotating plant. Such a duty does not leave much time for maintenance, and the problem of the right type of plant to install has been the subject of much investigation.

Motor-generators, rotary convertors and motor-convertors have all been used in the past, and of these the most successful is undoubtedly the large two-bearing single-commutator motor-

convertor, which, in service, is as efficient as the rotary convertor because there is no heavy loss in low-voltage a.c. connections, and is much easier to maintain because there are no heavy-current slip rings and a.c. brushes. The largest motor-convertors that have been used for this duty are rated at 4 500 kW and deliver 15 000–16 000 amp from one commutator at 250–300 volts when running at 231 r.p.m.

While the large motor-convertor was being developed for electrolytic service in this country, the mercury-arc rectifier was used in the United States, Germany and elsewhere for the same duty, though usually at much higher direct voltages, and, in view of this, the whole question was very closely examined in 1947, when an entirely new installation was projected for which there was no great restriction on the direct voltage to be used. The results of this investigation are given in Table 1.

the type. This rectifier, of British manufacture, is of the germanium type and is rated at 4 000 amp at 250 volts. It went into service in 1955, and, apart from certain initial troubles due to the failure of a number of individual units, it has been entirely successful and operates continuously on full load for long periods with negligible attention, the service efficiency being 96·8%. There is no doubt that the semiconductor type of rectifier will be the preferred one in future for electrolytic service.

Certain electrolytic processes require very large currents (40–50 kA) to be maintained at within ½% of the set value, and in these cases specially designed, separately excited motor-generators have hitherto been used, but it is very probable that in future semiconductor rectifiers will be employed.

To conclude this story of the development of converting and rectifying plant in Britain for electrolytic service, comparative

Table 1

COMPARATIVE PARTICULARS OF CONVERTING PLANT

	Motor-convertor			Mercury-arc rectifier: Ignitron type			Mercury-arc rectifier: 12-anode water-cooled steel-tank type		
Direct voltage	250	500	750	250	500	750	250	500	750
Efficiency, %	92·4	93·2	93·8	90·0	93·8	95·2	88·3	93·0	94·6
Relative floor space*	100	100	100	480	290	200	480	290	200
Relative weight*	100	100	100	250	175	140	250	175	140
Relative cost*	100	100	100	150	105	72	150	105	72

* These figures allow for all switchgear, transformers and auxiliaries and for any crane or other lifting equipment required.

From these figures it will be seen that, unless the direct voltage can be raised to 700–750, there is no case for the use of the mercury-arc rectifier, and, since the measures which must be taken to ensure the safety of the personnel in a cell room are much more onerous at 750 volts than at 250 volts, it was decided to continue at the lower value.

By 1949 the contact rectifier, which was in process of development in Germany before the war, was being perfected in the United States, and a trial machine of this type, designed for a continuous output of 10 000 amp at 210–260 volts, i.e. 2 600 kW maximum, was purchased from an American company, the transformer being of British manufacture.

This rectifier was commissioned in 1952, since when it has been in almost continuous service on full load, the overall availability, including maintenance periods, being over 96%, while the service efficiency averages 96·7%. Backfires occur very occasionally and are a disadvantage of this kind of rectifier, but contact damage is small and replacements can be made easily and quickly. Continuous running periods of over six months have been achieved, and the contact life is 6 000–8 000 hours.

The performance of this rectifier was so satisfactory that ten larger machines of the same type were designed and supplied by a British manufacturer. They have a continuous output of 15 000 amp at 220–270 volts, or 4 050 kW maximum, and all are now in service, six on a private system and four on the public supply. The performance has generally been very satisfactory, with high availability and a service efficiency of 97%, but those on the public supply have suffered from rather frequent back-firing arising from surges on the external system.

More recently, semiconductor rectifiers based on the use of germanium and silicon have been perfected, and as this type is very efficient at medium voltages, has no moving parts other than small fans and is immune from backfires, it was decided to install a small unit in order to assess the service performance of

properties of the favoured types are given in Table 2 for an output of 80 kA d.c. at 270 volts, while Fig. 1 gives the full-load efficiencies of representative types for an output of 4 000 kW at various direct voltages.

Table 2

CONVERTORS GIVING 80 KA AT 270 VOLTS

	Motor convertors	Mercury-arc rectifiers	Contact rectifiers	Germanium rectifiers
Efficiency, %	92·8	90·2	97·3	96·8
Power factor	1·00	0·94	0·87–0·90	0·88–0·92
Fault contribution, MVA	75	0	0	0
Crane capacity, tons	50	5	12	0
Area required,* ft²/kW	0·6	1·2	0·4	0·4
Volume of building,* ft³/kW	26	32	11	8
Relative cost*	100	139	79	74

* Allowing for all switchgear and auxiliaries.

Electro-Thermal Processes

Up to the outbreak of the last war, calcium carbide, which is made in arc furnaces, was not manufactured in this country because ample supplies were obtainable at low cost from Scandinavia, where cheap water power was available. The material was, however, a strategic one as it was required by the welding industry, and there was a growing demand for it in the manufacture of organic products such as solvents, plastics, etc. In order, therefore, to secure the position to some extent, the Ministry of Supply erected a large carbide works in South Wales in which were installed three 20 MVA 3-phase arc furnaces, while Imperial Chemical Industries built a 14 MVA furnace of the same type to meet part of their own requirements.

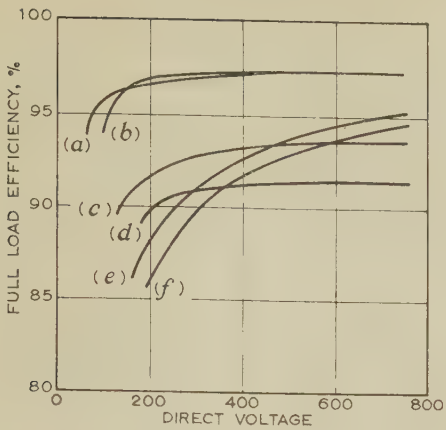

Fig. 1.—Efficiency of convertors for 4 000 kW d.c. output.

(a) Germanium rectifier.
(b) Contact rectifier.
(c) Motor-convertor.
(d) Motor-generator.
(e) Mercury-arc rectifier—ignitron type.
(f) Mercury-arc rectifier—12-anode steel-tank pumpless type.

Recently the latter firm has commissioned the largest calcium-rbide electric furnace so far built in this country. This has a pacity of 39 MVA and is supplied from the company's 33 kV stem in the area which is directly connected to the 132 kV Grid. The furnace is equipped with three 13 MVA single-phase FW 33 kV transformers fitted with on-load tap-changing gear ich is operated from the plant control room, the secondary ltage being in the range 152–256 volts. The primary and condary windings are normally delta connected, but there is ovision for off-load connection of the primaries in star for rting-up purposes. The secondary current is of the order of kA at 230 volts, so that the electrode current is about 100 kA. e connections to carry such heavy alternating currents must very carefully designed and constructed in order to reduce e reactance and losses to the economic minimum. The con-ctions between the transformers and the water-cooled electrode xibles each consist of sixteen 12 in × $\frac{3}{8}$ in copper bars, and e lead and return circuits to and from each transformer are erleaved, bar by bar, so as to obtain as low a reactance as ssible, the actual figure being about 2 100 microhms per phase 50 c/s.

The furnace itself is, for all practical purposes, non-inductive, d under normal conditions the power factor is 0·85–0·88. is is rather low, and an installation of capacitors may be quired to improve it.

On the earlier small furnace the e.h.v. circuit-breaker con-lling the supply was originally of the oil-break type, but, on count of the frequent maintenance required, it was replaced one of the air-blast type. The latter was, however, not tirely a success, and for the larger furnace a reversion to the -break type was made, but in this case a very conservative ing was selected and it has, so far, given satisfactory service, ough the oil has to be changed at fairly short intervals. The nace is arranged for automatic control so as to maintain the ee electrode currents equal and at the desired value.

Further large carbide furnaces are being erected in Britain, so t in the not too distant future the home demand for the oduct should be fully met by local manufacture.

Phosphorus is also made in this country on a large scale in hase arc furnaces, and while these tend to be smaller than rbide furnaces, the electrical problems are essentially the same.

Factory Distribution

Although the pattern of general load in a chemical works, i.e. workshops, general services, lighting, etc., is not very different from that in other industries, there are so many continuous processes in the heavy chemical industry which work day in and day out throughout the year and for which a power failure would be a very serious matter that special provision has to be made to ensure, as far as practicable, continuity of supply.

Primary distribution is usually at 6 or 11 kV, but in certain cases it has been found advantageous to use a superimposed 33 kV ring system to supply the secondary e.h.v. system through local switching stations.

Formerly, each substation was equipped with both high- and low-voltage switchgear, and, while this arrangement gave full local flexibility, it was expensive in that it required the use of local h.v. switchgear which in many cases had to be of heavy rating, i.e. 500 or 750 MVA at 11 kV, to suit the system conditions.

In recent years, therefore, conveniently sited e.h.v. switching stations have come into use, and these are connected to the main supply point by two or three feeders through reactors, thus enabling the breaking capacity of the e.h.v. switchgear to be reduced to 150 MVA at most. From these switching stations radial transformer-feeders supply each substation, so that e.h.v. switchgear is no longer required at these points.

The voltage generally used for local distribution is 420–440, and as with this voltage the breaking capacity of the m.v. switch-gear is limited to 30 MVA, not more than two 1 000 kVA trans-formers having an impedance of 5·5–6·0% may be used in parallel. Substation capacity has, therefore, to be based on the use of one or more separate groups of two 1 000 kVA trans-formers; two arrangements which have proved satisfactory are illustrated in Fig. 2.

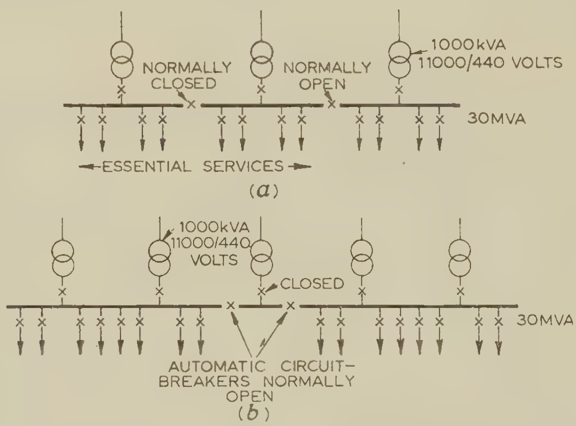

Fig. 2.—Arrangement of medium-voltage substations for the fault conditions not to exceed 30 MVA at 440 volts.

(a) Three-transformer substation: maximum load, 2 000 kVA.
(b) Five-transformer substation: maximum load, 4 000 kV.A

Plant distribution is through local m.v. switching stations, though large motors may be supplied direct from the e.h.v. system. Lighting supplies are kept separate and are given at 220/125 volts from 3-phase transformers in the plant switching stations. All m.v. supplies are fully metered in substations and plant switching stations.

Where large electrolytic processes are worked, a number of convertors or rectifiers will be required to run in parallel, and as the total current may well be 250–350 kA, the very heavy d.c. busbars required must be carefully designed if the voltage drop and losses are not to be excessive. In these cases, there will generally be three or four sections, each supplied by a group of convertors and connected to one another by fairly heavy power-operated circuit-breakers, but, as the section loads will normally be balanced, these need not be of greater capacity than 30–50 kA.

The economic current density remains fairly constant at about 670 amp/in^2, which is low enough to keep the temperature rise small so that linear expansion is slight and no special provision need be made to accommodate it. Present practice is to use 8 in $\times \frac{5}{16}$ in medium soft copper bars, and for a current of, say, 120 kA, 72 such bars are required, the overall width of each bus being about 45 in. Considerable space is thus required for the positive and negative bars. Full-face lap joints are used, as extensive tests have proved these to be appreciably more efficient than the fish-plate type.

On these heavy d.c. systems, a direct short-circuit does not cause much electrical trouble, as the time-constant is usually quite high and the actual fault current is relatively small in relation to the system capacity. Fire and similar risks arising from short-circuits must not, however, be underrated.

The accurate measurement of large direct currents under working conditions is not so easy as might be supposed, and the equipment normally available does not satisfy the rather stringent requirements of the process operators. The instrument department of Imperial Chemical Industries therefore closely investigated the matter, and they have produced a design of shunt which has a very low voltage drop combined with high accuracy and which does not deteriorate in service. The complete shunt consists of the requisite number of copper bars of standard cross-section into each of which is welded a very short length of a special resistance material having a negligible temperature coefficient. With a precision thread recorder connected to the shunt through a suitable averaging box, an overall error as low as $\pm 0{\cdot}33\%$ has been achieved, that of the shunt alone being $\pm 0{\cdot}15\%$. This design of shunt is giving most satisfactory service, and the low loss, e.g. 350 watts at 50 kA, is a decided advantage.

Flameproof Installations

Many of the processes in the chemical industry involve the use of inflammable gases or volatile liquids giving off such vapours, and very stringent precautions have to be taken to ensure freedom from explosion.

Although suitable electrical equipment can be obtained for a variety of the classified risks, it must not be overlooked that the type tests which are necessary to obtain approval of a design and an FLP certificate for it, are carried out on a rather limited number of gases, and these very often do not include the particular gas for which a flameproof installation is to be designed. A very onerous duty is thus placed on the electrical engineer responsible for the design and construction of the installation, and it is a pity that the chemical industry has so far not thought it desirable to establish its own testing station to provide reliable data for all the conditions likely to occur in practice.

There are three gases, namely hydrogen, acetylene and carbon disulphide, for which there is no equipment which can be regarded as safe, and in these circumstances all the electrical equipment must either be placed outside the plant, with the driving shafts passing through suitable sealing devices in the walls, or else it must be pressurized using an inert gas such as nitrogen, with means for automatically shutting down the plant in the event of failure of the gas pressure. The latter system may, in certain other cases, prove cheaper than the conservatively rated flameproof equipment available and is often used.

It may not be generally realized that, although a perfectly safe flameproof installation can be designed and constructed for most hazards, it by no means follows that it will remain so for long after it goes into service. This applies with great force to those plants in which there is a corrosive atmosphere, where the limiting gaps between machined surfaces and similar clearances may rapidly increase and so nullify the protection provided in the first instance.

A very heavy responsibility therefore devolves on the electrical maintenance engineer to see that flameproof installations are regularly and meticulously inspected and maintained, and this, in turn, calls for the employment of highly skilled and intelligent artisans having special knowledge and experience of the peculiar features of the equipment in their charge.

Staffing

Finally, a word or two may not be out of place about the staffing arrangements which, in my view, are desirable for the efficient and contented control of the activities I have described, for it often appears that there is a good deal of misunderstanding about how this important part of the work of the electrical engineer in the chemical industry is organized.

Until comparatively recently, it was customary in the smaller works to employ an electrical foreman to supervise the electrical work under the general direction of the works engineer, who, more often than not, had little or no knowledge of electrical matters. Later on, as the size of installations increased, electrical engineers came to be employed for this work, but they were regarded as people of minor importance and took a back seat in matters of organization and administration. In those days there was thus little or no future for a good electrical engineer in the industry.

With the rapid growth of the use of electricity in the industry, qualified electrical staff began to be appointed, and nowadays in a large organization there will usually be a separate and self-contained electrical department under the control of a well-trained and experienced engineer who is generally directly responsible to a director or may even be a director himself.

In a department such as this, all the senior positions will be held by experienced graduates, and every effort will be made to appoint similarly qualified men to the junior posts in order to provide for promotion, but in these cases a man having a good Higher National Certificate would not be overlooked.

There should be also a graduate apprentice training scheme under which three or four graduates are given a two years' course of training in the various branches of the department, and during this period they will usually be able to decide which branch of industrial electrical engineering they would like to follow.

I have only been able to touch upon some of the more important facets of the electrical engineer's work in the heavy chemical industry, but I hope I have said enough to show that it offers wide scope, plenty of opportunity and any amount of interesting work for well-trained and able electrical engineers.

CENTRE AND SUB-CENTRE CHAIRMEN'S ADDRESSES

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SOUTH MIDLAND CENTRE: CHAIRMAN'S ADDRESS

By G. F. PEIRSON, Member.

'RADIO AND THE NATIONALIZED FUEL AND POWER INDUSTRIES'

(ABSTRACT *of Address delivered at* BIRMINGHAM *5th October*, 1959.)

Vith the nationalization of the electricity supply industry in 48, the Midlands Electricity Board inherited as purchaser ders placed by the Gloucester Corporation undertaking for the ablishment of a base transmitting station in Gloucester, and the equipment of four of their vehicles with mobile radio. A annel in the 85 Mc/s band was allocated by the Post Office two-frequency working, whereby all the mobile stations nsmit on one frequency, to which the fixed station's receiver tuned, and the fixed station transmits on the other frequency, which all the mobiles are tuned. Messages sent out by the ed station are received by all mobile stations, but a message m any of the mobile stations is received only at the fixed tion. Mobile stations, therefore, cannot intercommunicate ectly; there are, however, occasions when it is desirable for em to intercommunicate, and this can be done by re-radiating nobile station's transmissions from the fixed station, the produre being known as 'talk-through'.

The Gloucester installation, commissioned in 1949, was ended to improve consumer service by enabling District fices to keep in touch with service vans, so that these could be uted most efficiently to take account of requests coming in er they had set off on their rounds. It soon became apparent at the system would also prove valuable for investigating eakdowns. When a failure was first reported by a consumer, stem control engineers had little indication of its extent, but an gineer was contacted and requested to investigate. With radio, was expected that he could be kept in touch with further erruption reports as they came in, which cumulatively would lp to pin-point the seat of the trouble.

Another anticipated use was that, if men were engaged on nstruction work, such as erecting overhead lines in a remote ot, and they were needed urgently to deal with a breakdown, alternatively, if an overhead line were out for maintenance d the system became overloaded, requiring the immediate toration to service of the line, radio could achieve this much ore quickly than if an engineer had to visit the site, see the men ar from the line, and report back before it could be switched in.

Such were the uses envisaged for system operation purposes; was, however, essential that there should be adequate radio verage of the area in order to maintain communication with personnel concerned.

The area of the Midlands Board is divided into seven Subeas, each of which is operationally self-contained and under control of an engineer operating from a system control centre. was decided that if radio were to be used for operational rposes, the transmitter must be under the control of the gineer on system control duty, thus giving him priority of use. hen it was not required for operational purposes, he would itch the equipment over to the radio-telephonist at Sub-Area ntrol for her to transmit messages from District Offices to the dio-equipped vehicles on consumer service.

Radio could be expected to be particularly helpful when toring supplies interrupted by lightning storms, which were own to affect electricity supplies in adjacent Sub-Areas nultaneously. Since the system controls in these adjacent b-Areas would need to deal with interruptions at the same time, different frequencies would be necessary for their transmitters in order to avoid mutual interference. The first step, therefore, was to apply to the Post Office for the allocation of separate channels for each of the several Sub-Area base stations. There would initially be ten mobile equipments associated with each base station.

At this time the Central Electricity Authority were using half of a two-frequency channel on a single-frequency-system basis throughout the country, almost exclusively for contact with repair parties working on their transmission lines, the advantage of this method being that an engineer in one vehicle can communicate with his patrolling repair parties at different points on a long line, and still keep the Grid control centre in the picture.

Other Electricity Boards, in addition to the Midlands Board, were seeking to use radio, and the Post Office asked that representations on behalf of all the Area Boards should be made through the then British Electricity Authority. This was discussed at an Area Board Chief Engineers' Conference in 1950, and a delegation of officers from the electricity supply industry was appointed.

Advice from manufacturers at that time indicated that to cover the large areas operated from one system control centre, channels in the 85 Mc/s band were necessary. However, when we discussed our problems with the Post Office it was clear that there were not sufficient low-band channels available, and the Area Boards were offered two channels in the 85 Mc/s and three in the 180 Mc/s band, the B.E.A. to continue to use half of another 85 Mc/s-band channel on a single-frequency basis.

By this time the V.H.F. Radio Committee of the British Electricity Authority and Area Boards had been established, and was given the problem of deciding how best use could be made of the channels allocated by the Post Office. A 'patchwork quilt' map was prepared showing the areas in which these five channels could be used over the country in a way which would result in the minimum of interference, with the two channels in the 85 Mc/s band allocated to areas with a difficult terrain, though subsequent experience has shown that the 180 Mc/s channels are almost equally efficient. The plan was accepted by the Post Office in September, 1951, for use by them when they received applications from Area Boards for channels.

In due course, tests were conducted and transmitters installed. To obtain adequate coverage, the transmitter often had to be located at a strategically high point, and was consequently remote from the control room associated with the transmission of its messages. The control room and transmitter, therefore, had to be linked, either by line or by radio. Wherever line could be provided, sanction could not be obtained for the use of radio, owing to the scarcity of channels. Because of this scarcity, when permission was given for a radio link, this had to be reverse-frequency working—namely the equivalent of a mobile transmitter and receiver being installed at the control room, communicating with the main transmitter, which would re-radiate the signal transmitted.

The objection to this system was that, each time one of the mobiles in the area wished to communicate with the control room, its messages would be re-radiated to all the other mobiles, quite unnecessarily. A certain amount of communication

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between mobiles is desirable, but this could be achieved by the controlled use of 'talk-through' instead of being indiscriminate, as is the reverse-frequency working of a radio link.

Area Boards were making increasing use of radio when the Postmaster General's Mobile Radio Committee invited the electricity supply industry to discuss with them the future use which the industry anticipated making of v.h.f. radiocommunication, and also the possible introduction of narrower channelling than that already employed, which was 100 kc/s in the 'high' and 'low' bands. At the meeting with the Mobile Radio Committee, we found that it was proposed to introduce 50 kc/s channelling in the less populated 180 Mc/s band, thereby doubling the number of high-band channels available for allocation.

When the report on frequency allocation was issued by the Postmaster General's Mobile Radio Committee in July, 1955, the electricity industry was making use of eight channels, the gas industry one channel, and the National Coal Board two channels—eleven in all. The report disclosed that the Mobile Radio Committee were of the opinion that, since the industries in question were fuel and power industries, the channels could conveniently be shared, and that the allocation could therefore be reduced from eleven to seven.

The Electricity Boards were amazed and dismayed by these views, because they were already finding their allocation too small for interference-free safe working. As adjacent system control areas must work on the restoration of supplies simultaneously, how much more necessary it must obviously be that in a given area both gas and electricity should operate simultaneously and independently of one another. Consequently, there was a vital need for gas to have similar allocations to electricity, and be independent of it, so that both could direct their repair staffs to deal with major disasters at the same time. Land subsidence might fracture gas mains and also damage electricity cables, with the possibility that such a catastrophe might cut off electricity supply to collieries, resulting in the need for the Mines Rescue Service to be brought in, in addition to the services of gas and electricity. All were equally important, and to delay any of them in the performance of their vital roles was unthinkable.

The Mobile Radio Committee's restrictive proposals resulted in the establishment of the Joint Radio Committee of the Nationalized Fuel and Power Industries, which was made responsible for preparing a report putting forward the views and requirements of the three industries. This report reviewed the experiences of the industries with their present allocation, and emphasized the danger-to-life aspect consequent upon the increasing number of instances where interference was being experienced.

Reference has already been made to the use of radio by the electricity supply industry; the requirements of the gas industry are similar, with the exception that their consumer service is, for the most part, limited to urban areas, and consequently the range of a given transmitter is not normally as great as that required by electricity. Gas Boards are also using radio for system operation, and with the development of the Gas Grid this may assume greater importance than it has to-day.

The coal industry makes use of its mobile radio for controlling its Mines Rescue Service. The same channel is employed throughout the country for this purpose, with the object of ensuring that wherever the emergency takes place, if it is of a major character, vehicles can be drafted from adjacent areas and be able to communicate with the local control without having to employ frequency switching. In addition to Mines Rescue, the Coal Board also has ambulance services and coal delivery transport vehicles.

In addition to the use of v.h.f. radio for mobile communications, the report of the Joint Radio Committee of the Nationalized Fuel and Power Industries also referred to the possible need for radiocommunication between fixed points for system protection and for the indication at manned central control points of switching operations and system load conditions occurring in remote unattended substations.

At the time the report of the Postmaster General's Mobile Radio Committee requiring 50 kc/s bandwidth equipment in the high band was published, at least one manufacturer was making equipment claimed to be capable of operating within 25 kc/s and, seeing the writing on the wall, the Electricity Boards decided that, rather than change from 100 to 50 kc/s channelling equipment and then have to change to 25 kc/s a few years later, no Electricity Board would buy other than 25 kc/s equipment, despite the fact that this narrower-bandwidth equipment would be used where the current Post Office specification permitted the occupation of 50 kc/s. This recommendation was also made to and accepted by the coal and gas representatives at an early meeting of the Joint Radio Committee of the Nationalized Fuel and Power Industries, and consequently the statement was made to the Post Office representatives that the industry were making for themselves elbow room within which to manoeuvre, and an early introduction of 25 kc/s channelling was pressed for.

Specifications were ultimately drafted to cover 25 kc/s equipment for use in the low band, thereby quadrupling the number of channels available, but even their due share of these would still not give sufficient channels to the fuel and power industries, as the greater part of their original allocation was in the high band. However, pending the general introduction of 25 kc/s channelling in the high band, the Mobile Radio Committee recommended the Post Office to permit the fuel and power industries to make use of the 25 kc/s spaces they had created in the intermediate positions between their existing channels.

Visits to various control centres in the Midlands were arranged for representatives of the Post Office and of the Mobile Radio Committee, to enable them to see for themselves the use which electricity makes of v.h.f. radiocommunication. These visits undoubtedly did much to smooth the way for their acceptance of the general principles in the report. Meetings were then resumed with representatives of the Post Office, and new 'patchwork-quilts' devised for the electricity and gas industries, making the best possible use of the channels, whilst at the same time endeavouring to achieve this with the minimum modification or change of location of existing equipment, also bearing in mind the requirements of the National Coal Board for Mines Rescue, ambulances and transport.

Whilst two types of mobile radio equipment have been manufactured and used, the majority of fuel and power installations have been of the amplitude-modulated type. Frequency modulation permits greater freedom from background noises, but the equipments are more complicated and difficult to maintain than amplitude-modulated types and also have other operational disadvantages in areas of low signal strength.

A practical problem encountered was that of coverage. V.H.F. radio waves are almost line-of-sight radiations, and in hilly country a mobile in a valley behind a hill can be out of touch with its base transmitting station. It is for this reason that relatively high sites are chosen for main transmitters. Where sufficient coverage cannot be obtained from a single point, two, and sometimes three, transmitters are employed, so sited that one or more are looking into each of the valleys. Radio engineers will appreciate the difficulty of operating three stations simultaneously on the same wavelength in close proximity to one another, and hence, when using 25 kc/s bandwidth equipment, station A works on the selected frequency, station B

rks 4 kc/s above it, and station C, 4 kc/s below, the mobile tion receivers being arranged to have sufficient bandwidth to eive all three transmissions. The 4 kc/s separation produces nigh-pitched whistle, but this can be removed by suitable ers without loss of clarity in the spoken messages.

Part of the report of the Joint Radio Committee of the tionalized Fuel and Power Industries was devoted to the ed for radiocommunication between fixed points to deal with emetering, or to enable control engineers at central control ints to be advised automatically of the conditions obtaining remote unattended substations, and also for system protion.

In the Midlands an installation has recently been established the protection of a 33 kV power line over a radio link. It erates by the measurement of the phase angle of the current wing in the line, the radio link being used to convey the ormation, namely the phase angle, after it has been converted o a signal suitable for transmission. The signal sent from the tiating end of the line is received at the opposite end and npared with the home signal, and if the signals differ the trip ay is energized.

The remote indication of switching positions and loads is required by the electricity industry, whilst the gas industry has need for the indication of the rates of flow in certain mains and the quantity of gas stored in gas-holders. Equipments using line connections have already been employed for this type of work, but owing to the remoteness of some substations, and the doubtful reliability of line connections which go in and out of a number of telephone exchanges, where they are liable to inadvertent disconnection by maintenance staff, the need for radio is certain. With this in mind, the Technical Sub-Committee of the Joint Radio Committee of the Nationalized Fuel and Power Industries has prepared a specification which has been discussed with the radio manufacturing industry to achieve standardization of equipment to meet this need.

In conclusion, one might say that radio in the electricity supply industry has been like so many other things—there were doubts initially as to whether it could be of much help; it was tried and it proved itself, and now we wonder however we got on without it. There is no doubt that still further uses will be found for it, which will result in increased efficiency and better service to our consumers.

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EAST MIDLAND CENTRE: CHAIRMAN'S ADDRESS

By D. H. PARRY, B.Sc., Member.

'SOME EXPERIMENTS IN ELECTRIC SPACE WARMING'

(ABSTRACT *of Address delivered at* LOUGHBOROUGH 6*th October*, 1959.)

In 1948, and for some years after, electricity generating plant s unequal to the demand and it was necessary to resort to d shedding and load spreading: coal was also scarce, and ny well-known figures urged that it was wasteful to use eleccity for space warming. I believed then, as I do now, that ctric space warming is the best means of defeating atmospheric llution and need not impose undue strain on national resources capital and fuel.

A doctor ought to take his own medicine, and in 1949 I comnced a series of experiments designed to improve the use of ctricity in our Leicester offices by removing demand from ak hours, by reducing consumption and by improving comfort.

At Leicester Lero Depot, radiant electric fires in offices and rkshops were replaced by central heating employing hot-water rage and conventional hot-water radiators. The installation mprises a storage tank heated during off-peak hours to 190° F, ntrolled by time switch and thermostat. During office hours, rm water is circulated by pump through small-bore piping the radiators, and steady temperatures are maintained by side and outside thermostatic control. This installation is ost successful; it is interesting to many people who are accusmed to heating by hot-water radiators and wish to avoid the isance and dirt associated with solid fuel or oil. Some ners of centrally heated buildings have replaced fuel-fired ilers with a small electrode boiler, and for background heat t-water storage can often be dispensed with in a substantial ilding. If the building fabric can provide sufficient heat rage, there is no advantage in using water to circulate heat; bles, embedded in the fabric, preferably the floor, are a cheaper ethod and give more radiant heat than conventional hot-water diators. Improved heat insulation of a building reduces electricity consumption and enhances the heat storage of the fabric.

In an Institution paper published in 1951, I suggested that a combination of efficient heat insulation and floor warming offered the best solution for providing comfortable warmth in a modern domestic dwelling for a moderate capital cost and without excessive electricity demand. Improved heat insulation and floor warming are now both making encouraging progress in modern building, and a wide experience of technique is available to architects and builders. Floor warming is much appreciated by those with direct experience, but as we are to have a paper by Mr. Moule on this subject later in the present season, I do not propose to discuss details here. I must, however, comment on the suggestion often made that floor warming is not suitable for existing houses, or in rooms with suspended wooden floors, or where floors are covered with thick carpets.

On behalf of the Electricity Council, an experiment is in progress at the St. Matthews Estate, Leicester, on the use of block-storage heaters in domestic dwellings. These heaters are not at present sold for use in domestic dwellings, but may become available if and when agreement with Customs and Excise is reached concerning purchase tax. The tenants appear to be very satisfied with the operation of these off-peak heaters, and for those householders who like an obvious factory-made heater and wish to avoid interference with floors and decorations, this would be a satisfactory solution. But it may be doubted whether block heaters give the same comfort as floor heating and they do occupy valuable space.

Where there are solid partition walls, panels plastered to the walls offer an alternative, and in my own house, wall panels installed eight years ago in three rooms, controlled by time switch and air thermostat, give excellent background heating and show no sign of failure. Two years ago I installed background

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heating in the hall by the simple method of chasing the plaster to receive a heating cable. This made a neat concealed source of warmth which shows no sign of failure.

The idea of using massive walls for heat storage led to an experiment of painting walls with an undercoat of colloidal-graphite paint to be used as a resistance element, and two rooms in the East Midlands Electricity Board's offices have been treated in this way. In the large room a strip of wall measuring 2 ft by 64 ft and running horizontally under the windows was painted with graphite between copper-strip electrodes and afterwards painted with cream-coloured flat oil paint to match the original colour of the wall. The applied voltage is 100 and the total loading of $3\frac{1}{4}$ kW gives a pleasant supplementary warmth in a room with a cold aspect. This heating has been in successful operation for five years and is very suitable for an office where unobtrusive warmth is a great advantage—a hot-water radiator or similar appliance is such a clumsy and untidy device. Unfortunately, this method of heating requires excessive skill in applying paint because the thickness of paint is critical and must be exact and uniform over the whole area, but I see no reason why graphite or other conductor, sandwiched in a factory-made wallpaper, should not prove a convenient method of room warming in either new or existing buildings.

Temperature regulation by opening or closing windows is a wasteful habit which should be unnecessary when using electrical warmth, but continuous ventilation is necessary and may be controlled by the use of forced- and induced-draught fans, together with inlet and exhaust air-ducts; heat may be recuperated by means of a heat exchanger.

Bradbourne Road depot of Leicester Sub-Area, a building very like a private house, was originally designed for heating by electric tubular heaters and radiant fires. Switching off during peak hours caused a serious drop of temperature. In this building, insulation was improved by adding roof insulation, a skirt of Onazote round the walls at ground level and double windows. Ventilation was looked after by inlet and exhaust ducting to the different rooms, together with forced- and induced-draught fans with a suitable heat exchanger. These alterations resulted in a substantial saving of electricity, improved the comfort in the building and made it feasible to switch off during peak hours.

The construction of three major substations named Salutation, Devana and Jupiter, with outside transformers of similar size and loading gave opportunities of comparing different methods of warming unattended switchrooms. Full comfort conditions are unnecessary, but a margin of 5° F above ambient temperature prevents condensation.

The first substation, Salutation, was provided with direct electric heating in the switchroom controlled by a humidistat, but this proved unsatisfactory probably owing to abnormally damp subsoil. Devana and Salutation switchrooms were therefore equipped with warm-water radiators which obtained heat through oil-to-water heat exchangers from the transformer losses. Ample heat is available and the pumps are run only at off-peak times. But the night load on the transformers is small and the oil temperatures are very moderate, so that generous heating surface is necessary in the switchroom radiators. Thus a saving of £200 in the cost of electricity is cancelled by a similar increase in capital cost. As the direct heating of Salutation switchroom had proved inadequate, it was replaced by another method of tapping the waste heat from the main transformers. The low-grade heat could be promoted by means of a heat pump, and for the modest temperatures needed, standard commercial refrigerator units could be used. The apparatus is simple, consisting of four motor-driven condenser units in the switchroom using Freon 12 as refrigerant to convey heat from evaporator units clamped to the transformer tanks. But it provides ample heat in the switchroom, with an average performance ratio of 5·23.

The substations of Salutation and Devana are almost identical in dimensions of the switchroom and loading of the transformers and the performance of the heat-pump and heat-exchange methods of tapping waste heat can be directly compared when it is seen that the heat pump provides the best performance at the lowest annual cost.

The Jupiter substation has a more compact layout and the heat exchanger provides more heat than the apparatus at Devana and some heat is now taken to nearby offices for space warming.

The waste heat available at these substations would be sufficient to provide full comfort conditions in an attended substation or in a small depot, and this must often be the case with a major substation. Commercial refrigerating plant is very reliable, and it may be suggested that in many instances the very bulky transformer-oil coolers could be replaced by standard refrigerator units, located in an adjacent building for heating purposes with the evaporator coils immersed in the upper transformer oil. An attractive feature of this source of heat for space warming by heat pump is that it is to some extent self-regulating; transformer copper losses are at a maximum in cold weather because of the heating load on the supply network.

In a switching station with no waste heat available from associated transformers, condensation may be defeated by increased ventilation provided that the temperature in the substation is maintained by making good the additional ventilation losses. This can be done by means of a heat pump working on the air cycle, consisting of a motor-driven air compressor, an air engine and a heat exchanger. A machine that I purchased for this purpose, though rather crude, demonstrates that such a heat pump would be useful for space warming where considerable ventilation is required. The heat pump has a performance coefficient exceeding unity, and in addition the heat exchanger recovers heat from the ventilation air which would otherwise be rejected.

In 1958 an engineering depot was built at Guthridge Crescent, Leicester, and a heat pump installation was provided to heat the offices, taking heat from a supply of warm water piped from the heat exchanger in Jupiter substation to which I have already referred. Again standard refrigerator condensing units are used and heat distribution is by auxiliary fan which circulates air through the condensers and the offices. The installation is designed for a performance ratio of 3, and whilst no official test has yet been made there is no doubt that the apparatus gives ample heat and is very satisfactory in operation.

The vapour-cycle heat pumps described have available a heat source at an elevated temperature and therefore give a high performance ratio with a moderate capital cost. In the ordinary building no attractive source is at hand; the most practicable source is the earth, but a large area and considerable expense and complication are necessary to collect the low-grade heat available. If atmospheric air is the source, the fall of source temperature and the formation of ice reduce output and efficiency at times of severe cold when heat is most desired.

I installed a small experimental heat pump in my own house two years ago to provide hot water, using ventilation air and house drains as the heat source; but I found that, whereas at average temperatures a performance ratio of 3 was obtained, this fell to unity and the heat output to one-third in cold weather. In really severe weather the performance ratio fell below unity and the heat pump became a heat leak. The plant was therefore abandoned.

A larger plant would give better results, but loss of efficiency and output at low temperatures are fundamental weaknesses of the vapour-cycle machine, and therefore a heat pump of sufficient

tput to meet the maximum heating demand must be an pensive machine.

Nevertheless, there is a promising field for the heat pump in ge buildings in the centre of a built-up area where off-peak rage load would exceed the normal peak load and require usual capital expenditure for electricity supply.

It appears to me that the air-cycle heat pump is worthy of more ention for the space warming of large buildings. The theo-ical performance is not so high as for a vapour cycle; in ictice it may not exceed 1·5, but there is the added advantage it ventilation of buildings can be combined with heating and heat usually lost in ventilation air is recovered. This advan-ge increases with lower temperatures, so that the air cycle ng atmospheric air as a heat source does not suffer loss of iciency and output to the same extent as a vapour-cycle pump. a large building, ventilation losses assume a higher proportion the heat loss to be made good by the heating installation, and refore the air-cycle pump may give a higher thermal efficiency in a vapour-cycle pump, and because of greater simplicity ould have a lower capital cost.

In a small building, such as a domestic dwelling, heat losses from the fabric are the major part of the total, and floor warming combined with good heat insulation appears to be the economic method of heating by electricity.

In a large building a heat pump could have an overall thermal efficiency exceeding 75% for the coal burnt at the power station, which is better than the performance of fuel-fired central-heating plant, and moreover the power station has tall chimneys and is usually remote from city centres.

I have little doubt that the heat pump offers the best prospect of defeating atmospheric pollution in large cities, but at present fuel prices the capital cost of the plant makes it uneconomic.

Fuel resources are at present abundant, fuel prices are depressed and there is little enthusiasm for fuel saving. But world demands for fuels are increasing so rapidly that it can only be a few years before it must again be economic to expend additional capital for fuel saving. It would seem wise to continue to experiment with the heat pump, and I would like to see the electricity supply industry undertake a large-scale experiment of heating a city store or office block using an air-cycle heat pump.

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WESTERN CENTRE: CHAIRMAN'S ADDRESS

By H. JACKSON, B.Sc.(Eng.), Member.

'DEVELOPMENT OF INDUSTRIAL LOAD'

(ABSTRACT *of Address delivered at* CARDIFF 12*th October*, 1959.)

The promotion of increased sales and the general development the use of electricity is the primary function of the commercial e of the electricity supply industry. Many of the duties ried out by those engaged in such work, particularly in con-ction with the development of the industrial load, call for a t inconsiderable degree of technical ability and a wide perience of the practical utilization of electricity; in short, it a job for a trained engineer. Moreover, to advise a consumer a scheme which may cost several hundreds of thousand unds involves a high level of personal responsibility.

It is the author's hope that this review of the development the industrial load will come to the notice of some of our ident and Graduate Members, and that it will stimulate their erest in the scope which undoubtedly exists for a satisfying d rewarding career on the commercial side of electricity supply.

During the year ended 31st March, 1959, industrial supplies counted for 49% of the energy sold and nearly 42% of the enue received by all the Area Electricity Boards. For the uth Wales Board the figures were 73% and 64%, respectively. ese figures clearly demonstrate the important place occupied the industrial load in the economy of the electricity supply lustry in this country as a whole and in South Wales in rticular.

Before considering the present pattern of industrial utilization d the possible future scope for expansion, let us look in rospect at the growth of the industrial load.

In the first two or three decades after the commencement of olic electricity supply, for reasons which are easy to appre-te, the use of electricity in industry developed slowly. The break of the First World War, however, brought about con-erable acceleration of the rate of development. By this time ad been realized that the direct-current systems upon which rly all the early distribution undertakings had been based imposed severe limitations on the use of public supply for industrial purposes, and from then on alternating current was acknowledged to be the only practicable system for large-scale supply.

Unfortunately, however, individual undertakings, of which there were approximately 600, had developed their own systems without regard to those of others, and progress was retarded by the existence of many different voltages, frequencies and systems. This lack of co-ordination was one of the first things to which the attention of Parliament was addressed after the cessation of hostilities. The setting up of the Electricity Commission under the 1919 Act and of the Central Electricity Board under the 1926 Act, which also promulgated a standard frequency of 50 c/s, greatly facilitated the more rapid electrification of industry.

Early developments in the use of electricity in industry were confined to lighting and the replacement of gas, steam or oil engines for driving lengths of line-shafting. Many of the new factories which were equipped for the manufacture of munitions during the 1914–18 War were, however, planned on the basis of electrical drives throughout. It was at about this time that the practicability of electricity as a source of heat for industry began to be seriously explored. Several direct arc furnaces, small ones by present standards, were installed in steelworks for the melting and refining of steel.

The twenty years between the two world wars saw many advances in the application of electricity in industry. One of the most spectacular achievements of this era was the development of the thermionic valve in its various forms, which gave rise to a whole new series of techniques under the general heading of 'electronics'. Meanwhile the development of arc and induction furnaces and of infra-red and of resistance heating was proceeding steadily, and considerable progress was made in the technology and practice of welding.

Early in the Second World War it became apparent that our survival as a nation was dependent on the maximum possible

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production of war material, and it is no exaggeration to say that electricity was one of the most important factors in achieving that aim. The pressing need for ever greater production in order to secure our survival provided a stimulus in which the pace of industrial development was accelerated to a degree never previously achieved.

The slight recession in the sale of electricity for industrial purposes which followed the termination of the war was the inevitable result of the greatly reduced need for war material and the time necessary to convert and adapt munitions plants to peace-time production. The need for the revival of our export trade and the demand for consumer goods at home were so urgent, however, that in a remarkably short time the demand for electricity was again on the upward trend, and before long we were in the position that, owing to the almost complete war-time suspension of generating-plant construction and the length of time required for the building of a modern power station, the generating resources of the country were unable to meet all the demands of consumers. The era of load shedding and load spreading followed.

The job of the electricity sales engineer at that time, whether in the industrial, commercial or domestic field, was a difficult and in many ways an unenviable one. In the event, particularly in the industrial sphere, our sales and development engineers did an excellent job. Their services were particularly devoted to visiting industrial establishments and advising managements on load spreading and replanning of processes, thus minimizing the need for load shedding and at the same time improving the load factors of individual consumers, thereby reducing their electricity costs. In this way many valuable and lasting contacts with industrialists were established, and the seeds thus sown have borne, and will without doubt continue to bear, very good fruit.

Although the war ended in 1945, unrestricted promotional activities were not resumed until about 1954. Among the many advances since that date, one of the most outstanding has been the development of devices based on semiconductors, such as transistors and rectifiers. The design of electronic equipment of all types is in process of undergoing considerable change. In modern electronic circuitry, transistors are replacing thermionic valves, with a substantial saving in space and in cost of maintenance; and germanium and silicon rectifiers, with their higher efficiencies, are replacing selenium rectifiers.

Let us, then, take stock of the present position in relation to the practical applications of electricity for industrial purposes.

For many years there has been no radical change in the basic design of motors, although, of course, there have been detailed improvements. In motor control-gear, however, there has been a development of great significance. Electronic control now provides a very high order of accuracy for variable-speed drives and for the co-ordinated speed control of multi-motor equipments, such, for instance, as those associated with the rolling of steel strip and with paper machine drives.

Other techniques based on electronic principles which are now available to the industrialist include ultrasonics for thickness measurement, flaw detection, cleaning, etc.; closed-circuit television for remote viewing where close inspection is not possible or safe, or where a number of separately situated operations are required to be controlled from a central point; and computers for data processing, the solution of intricate design problems, the control of machine-tools individually or in groups, and mechanized accountancy.

For many years motive power was indisputably the major usage of electricity in industry, but to-day, although it would be difficult to find statistical proof, there would seem to be more ground for believing that this role has now been taken over by electrical heating. Certainly the range of electrical heating equipment which is now available to industry is very extensive. Advances in this field have provided the industrialist with a wide range of extremely versatile equipment. There must be few industrial products which at some stage of their manufacture do not require the application of heat, and it is surely not overstating the case to say that there are very few of these heat processes which cannot be performed by one or other of the electrical methods more efficiently, more conveniently, more cleanly, more quickly and, in many cases, more economically than by any other means.

As a means of producing heat, electricity can be considered as a fuel having varying degrees of refinement according to the method of conversion and utilization. For instance, at the coarser end of the scale we have the arc furnace using large quantities of energy, while at the other end there is high-frequency induction heating for small components frequently placed directly in the production line, with high-accuracy process control and relatively small consumption. In between there are direct and indirect resistance heating for furnaces and ovens with heat transfer by conduction radiation or convection; infra-red heating, mains and medium-frequency induction heating and, in addition, outside this range, what may perhaps be considered as the most refined form of all, namely very-high-frequency dielectric heating.

With any of these electrical methods of heat production and utilization we may have any one or a combination of several forms of control, e.g. manual, thermostatic, pressure, speed, time, energy regulation, etc., and according to the degree of precision required various of these automatic controls can be of the closed-loop type using electronic equipment. Frequently a process may present a choice between two or more of the various methods of heating or types of control.

Attention to the potentialities of the industrial heating field has not been confined to electricity, and the intense competition from other fuels can be met successfully only if the efficiency of electrical industrial heating equipment is matched by equal efficiency in the supply industry's sales organization and methods. Personal contact with the chief executives of industrial concerns is the keynote, but it is essential that the electrical sales engineer should have a fairly intimate knowledge of many industrial processes and be able intelligently to discuss production methods, techniques and problems. In addition to technical skill and experience, however, he must have the kind of personality which inspires confidence in his ability to provide reliable and impartial advice.

It is important that Electricity Boards should see that their student apprentice and post-graduate training schemes do not neglect the need to discover and encourage young engineers who have an inclination towards, and the qualities necessary for, industrial sales development.

Electricity tariffs are naturally a very important factor in load development although in some applications price is of less consequence than in others. Electric motive power and lighting, for example, have for many years had no serious competitor. In some sectors of the industrial heating field also the advantages of electricity over competing sources of heat are so great that the price of electricity is not extremely critical. This would apply, for instance, to high-frequency induction heating for the hardening or heat treatment of small machine components in a continuous production line, or to various forms of resistance welding.

There are, however, several electrical heating processes where the cost of electricity is all-important, and in the main these are associated with heavy-current equipment such as arc and induction melting furnaces, where the cost of energy is an appreciable percentage of the total cost of production. Fortunately

ny of these heavy-current processes can, under controlled nditions, tolerate temporary reduction or even cessation of pply without any serious effect on the product, and this offers pe for some flexibility in methods of charging.

t has frequently been noted that, since the very early days, the nsumption of electricity has more than doubled every ten rs. What of the future? As yet there is no indication of any ninution in this remarkable rate of development. Not only is field of usage of electricity in industry still expanding, but ustry itself is also expanding very rapidly. Many large ustrial projects are under construction and others under nsideration.

The trend of the cost of electricity supply towards a higher mand component and a lower running component may be pected to continue, and this will lead to a reduction in the erall average cost per unit, particularly for high-load-factor supplies. There is reason to believe, therefore, that there are good prospects for load development, especially in those industries where two- or three-shift working is normal. The kinds of development which can be envisaged include electrothermal applications in metallurgical processes, particularly those in which load control can be expected, such as ore smelting, and also electrochemical processes.

This review of progress and prospects in the development of the industrial load is by no means an exhaustive one, indeed it is little more than an outline sketch. It is the author's hope, however, that sufficient has been said to show that the industrial section of the commercial department of an electricity supply undertaking can offer an interesting and exciting career to any young electrical engineer with a sound technical training who is prepared to devote a few years to acquiring experience in industrial utilization and production techniques.

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EAST ANGLIAN SUB-CENTRE: CHAIRMAN'S ADDRESS

By D. H. McCRACKEN, B.Sc.Tech., Member.

'RAILWAY ELECTRIFICATION IN GREAT BRITAIN'

(ABSTRACT *of Address delivered at* IPSWICH *5th October*, 1959.)

The early tube railways of London, such as the City and South ndon, the Waterloo and City and the Central London, which ne into operation at the end of the 19th century, used direct rent with insulated conductor rail and running-rail return. e same system was used on the Liverpool Overhead. In both ndon and Liverpool, earth-leakage currents caused serious turbance to Post Office telegraph circuits, while at Greenwich servatory the Admiralty magnetometers became almost readable. Parliamentary legislation of 1900 insisted upon an ulated return conductor being used in the region of Greenwich, d as a result the 4-rail system was adopted and became ndard practice on the London underground railways. Advanges accruing to the operators included the ability to run for rt periods with an earth fault on the positive, and full freedom use the running rails for track circuiting. The Metropolitan d District Railways had great difficulty in deciding whether to d.c. 4-rail or 3-phase a.c. with two overhead conductors on ir systems, which included the jointly owned Inner Circle. entually the Board of Trade ruled in favour of direct current.

Third-rail systems at voltages up to 600 volts were introduced the suburban regions of Newcastle and Liverpool. Rather er the London and South Western Railway electrified the ames Valley lines on this system. By the time these lines ne into operation, in 1915, the Admiralty magnetometers d been removed from Greenwich, but more careful attention rail bonding and the use of negative feeders greatly reduced erference and corrosion troubles due to leakage currents.

t was generally appreciated that the capital costs of electrifican could be significantly reduced by adopting a higher voltage. C. systems using single-phase low-frequency current collected m an overhead contact wire were operating successfully in rope and America, and two such systems came into being in gland. The London, Brighton and South Coast Railway ctrified its suburban lines using 6·6 kV 25 c/s with an overhead tact wire supported by double catenary. The original train ipments used compensated repulsion motors of German manufacture, but after 1914 similar equipments were supplied by a British firm. The Midland Railway electrified a short route from Lancaster to Heysham and Morecambe using 6·6 kV 25 c/s collected from a compound catenary overhead system. Compensated series motors were used on the three trains originally put into service. Aspinall of the Lancashire and Yorkshire Railway and Raven of the North Eastern Railway both favoured high-voltage direct current. The former experimented successfully with 3·6 kV overhead, but eventually used 1·2 kV side-contact third-rail for the Manchester to Bury line. Raven favoured 1·5 kV overhead and used this system on the first electrically operated mineral railway in this country—the Newport to Shildon line, which ran successfully until 1935. It was Raven's intention to electrify the main line from York to Newcastle at 1·5 kV, but the grouping of the railways in 1923 resulted in the project being dropped. One result of this grouping was the absorption of the London, Brighton and South Coast Railway into the Southern Railway, which thus found itself operating two systems, a.c. and d.c. In the interests of standardization the a.c. system was changed to third-rail d.c., the work being completed by 1929.

The Pringle Committee, which was formed to study railway electrification systems and to recommend future policy, reported in 1928 in favour of direct current at 750 volts or 1·5 kV with a proviso that 3 000 volts would be acceptable in special conditions. There followed the Manchester to Altrincham and the Liverpool Street to Shenfield electrifications using 1·5 kV d.c. overhead contact wire supported by compound catenary. Many of the early electric railways generated their own power, more often than not in the form of 3-phase a.c. at 25 c/s or $33\frac{1}{3}$ c/s, rotary convertors being used to provide the direct current for the trains. After 1928 it became general practice to purchase energy in bulk as 3-phase 50 c/s and to use rectifiers in line-side substations.

The Manchester, Sheffield, Wath lines commenced electric working in 1954. This was the first main line electrification at 1·5 kV. Locomotives were used, and because of the long severe gradients regenerative braking was provided for.

The plan for modernization and re-equipment of British

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Railways published in 1955 and now well under way provides for a change-over of motive power from steam to Diesel and electric. Work is proceeding on the electrification of three major routes: Euston, Manchester, Liverpool; King's Cross, Doncaster, Leeds; and Liverpool Street, Ipswich, Clacton, Felixstowe. The system of electrification to be used was subject to thorough study, and it was realized that very significant capital savings could be made by using high-voltage a.c. of standard frequency. The French National Railways began to experiment with 50 c/s in 1950, and results were so promising that major electrifications were carried out on lines in north-eastern France. In this country the Lancaster to Heysham line was taken over for experimental work on 50 c/s traction, and by March, 1956, Sir Brian Robertson was able to announce that the standard for all future electrification would be 25 kV 50 c/s a.c.

The Colchester, Clacton, Walton line has been thus electrified and commenced service in April, 1959, and the Crewe to Manchester section of the main route from Euston is nearing completion. No doubt many types of train equipments will be put into service; mercury-arc rectifiers, germanium and silicon rectifiers are all being subjected to extensive trials and are applicable to both multiple-unit stock and locomotives. It can only be assumed that, as more operating experience is acquired, electrical and railway engineers will be able to standardize on two or three types of equipment best fitted to meet the needs of service on British Railways.

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NORTH-LANCASHIRE SUB-CENTRE: CHAIRMAN'S ADDRESS

By O. SEYMOUR, Associate Member.

'EDUCATION AND ELECTRICAL ENGINEERING'

(Abstract *of Address delivered at* Blackburn 14*th October*, 1959.)

The purpose of technical education is twofold—to train engineering or scientific personnel for their work in a branch of their chosen profession, and to provide a broad educational background which will be of value when problems, other than technological, have to be resolved. By their manifold activities and schemes of training, technical colleges have a co-operative part with industry. Thus provision is made for research workers, development or production staff and also for management and commerce personnel. At every stage the departments of technical colleges are able to assist industry so far as training is concerned, to the ultimate advantage of the community. It is intended to consider some aspects of technical college activity with reference to electrical engineering.

Engineering is an art as well as a science, since industrial practice has sometimes preceded theory. It is, however, an art in which knowledge and experience play a vital part, and it has been said that 'An engineer must have a good appreciation of the degree of accuracy which is necessary in his work. Insufficient accuracy may lead to wrong and dangerous conclusions; excessive accuracy causes waste and delay'.

Following the Industrial Revolution there grew up a demand for education which resulted in the formation of the mechanics institutes and scientific societies, particularly in the North of England, part of whose work was to make good earlier educational deficiencies. The activities of these bodies gradually declined and except for a few they disappeared. However, since the time when evening classes only were available for instruction in technical subjects we have had the development of part-time day courses and 'sandwich' courses. Thus apprentices and other workers of suitable aptitude have received training in subjects appropriate to their profession or trade enabling them to obtain recognized qualifications.

Considering the pattern of electrical engineering courses in particular, the relationship between courses and the possibilities of transfer between courses, the following additional points become noteworthy:

> The increasing attention given to basic instruction in trade or craft subjects in secondary technical and secondary modern schools is gratifying, since students are enabled to show aptitude for a particular skill and the choice of subsequent employment is less haphazard.
>
> Ample provision exists for transfer of a student from one course to another upon the completion or part completion of his original course.
>
> The attainment achieved by a particular student is limited only by his own ability, but it should be remembered that working and domestic circumstances are a dominant influence especially in the case of adult students.

In professional and trade courses in electrical engineering there appears to be the need to introduce additional studies variously called the 'humanities' or liberal studies, the aim of which is to produce

> Clarity of thought with precise and purposeful expression, orally or in writing.
>
> An appreciation of other forms of artistic expression (literature, music, painting, etc.).

It is indeed to be hoped that the tendency to include such studies in courses will continue.

In considering the factors to be taken into account in the development of a new college as a whole, the specialist work of the electrical engineering department will occupy the energies of its staff, and since it is this department which is of particular interest here, some consideration is given to its requirements.

The department's workshops and laboratories are, for preference, best housed on the ground floor with the interposition of science laboratories between installation workshops or machine laboratories and any classrooms at hand. Vigilance is required to ensure that the installation of cable ducts, electrostatic screening and special wiring requirements are brought to the attention of the architect. In addition, it is desirable to anticipate as far as possible future requirements and to plan accordingly.

In deciding upon a particular method for the electrical distribution system to be employed, certain general principles can be laid down:

> Whatever system is adopted, it must be simple, safe and flexible and without unnecessary complication, bearing particularly in mind the needs of part-time staff who will not daily be operating the system.
>
> The wiring for each laboratory should be independent of others, leaving provision for future extension where this is likely to be required.
>
> An orderly arrangement for a machines laboratory or workshop is desirable, not only to enhance architectural features, but, more important, to encourage orderliness in the practical work undertaken by students. Only in very special circumstances should trailing cables be permitted.

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It is considered that all supplies should be isolated from the mains to reduce shock risk, with the use of a mains transformer to limit the maximum alternating voltage to about 230 volts between lines. A similar limit should exist for d.c. supplies.

Laboratory Distribution Systems

The choice of distribution system depends upon the type of ɔoratory to be supplied and the number of groups of students be accommodated. Individual preferences are often evident laboratory wiring schemes, but the following are the general ethods in use.

Independent supplies with separate interconnectors.—This is a mewhat rigid system which is suitable for laboratories where oups of bench experiments are conducted. Some flexibility available by arranging for interconnectors to link up the bench sitions.

Ring-Main System.—The various supplies are distributed und the laboratories by ring mains. Auxiliary ring mains, th section isolators, are provided for interconnection and oarate supplies, but are not associated with any particular pply. Change-over switches enable supplies to be obtained om either the main busbars or the auxiliary busbars.

Radial system with plug-and-socket connections.—This is considered the simplest, most flexible and adaptable in use. Each circuit is supplied, via fuses or miniature circuit-breakers, from a central distribution plug board, resembling a large-scale telephone switchboard, at which all mains and battery supplies are available. Connector busbars are provided at the plug board enabling the interconnection of outgoing circuits. These circuits terminate with shrouded sockets at the plug board and with rotary switches at the bench or machine position, the wiring between preferably being installed in underfloor trunking.

This system is ideal for larger electrical machines or power laboratories on account of the ease with which interconnection between benches or machines can be made. Connections to plug-board supplies are localized, and all outgoing circuits are under easy control of the laboratory staff.

It is not enough to provide adequate laboratory facilities: teaching skills must be fully employed by full-time and part-time staff alike, making use of demonstrations and visual aids of all kinds. One hopes that, in the future, the student studying under part-time day arrangements may be able to broaden his general educational background by assimilation of the so-called 'liberalizing' influences so that he may become, not only a well-trained technician, but one whose general education makes him desirous and able to serve his fellow-men.

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SOUTH-EAST SCOTLAND SUB-CENTRE: CHAIRMAN'S ADDRESS

By D. M. THORNTON, B.Sc., Member.

'SOME FEATURES OF A SUPPLY ENGINEER'S WORK IN THE LESSER POPULATED PLACES IN SOUTH SCOTLAND'

(ABSTRACT *of Address delivered at* EDINBURGH 20th *October*, 1959.)

Let us first consider briefly the type of engineer best suited to tribution work in the remoter parts of our country, with rticular reference to the hills and valleys of the Scottish rderland. He must, first and foremost, be a good all-round tribution engineer, but in addition he must have a sound rking knowledge of farming to enable him to converse elligently with the many farmers he will undoubtedly meet in course of his duties. He must also have a good working owledge of the various Acts of Parliament that continually p up—the Electricity Acts, the Town and Country Planning , the Factory Acts, to mention but a few. In addition, he st be something of a diplomat, as many of the people with om he will have to deal often require to be handled very lomatically indeed.

o much for the man himself. What of his work? This falls ly logically into three categories, planning, construction, and ration and maintenance. I propose therefore to review efly some of his work and worries under these three headings.

n the planning stages he must have a clear picture of what has, appreciate fully what he is being asked for, and at all es have a clear picture before him of the ultimate future elopment of his territory. The most unpredictable things are to happen. Perhaps an industrialist from the overcrowded ts of the country suddenly decides to build a factory miles n anywhere and to call for a load of countless megawatts place where the mains are either hopelessly inadequate or do not exist, and so the slide-rule and drawing-board have oe brought out and just another of those jobs has to be dled. One of the most spectacular results of the nationalization of the electricity supply industry is that the big cities are now able to help their country cousins. This has given rise to the launching of an intensive rural development programme all over the country. Distribution mains are rapidly spreading to the highways and byways and up to the heads of the most remote valleys where only a few years ago a public supply of electricity was merely a dream. In big urban distributions one can have a potential consumer every few yards, but in the remote hill-lands one has often to provide several miles of mains to supply a solitary consumer. To give you some idea of the type of country to which I refer I should like to show you a few illustrations.

[Here were shown twelve coloured views mostly at or near the heads of some of the many radial valleys in the Ettrick Forest region.]

Obviously the taking of an electricity supply to such places cannot be an economic proposition, but the Electricity Boards are pushing ahead with the provision of such supplies as part of their moral and legal obligation to the community as a whole.

Not only has a job to be planned electrically and geographically, but it has also to be costed in order to obtain the necessary sanction to spend the capital involved. No matter how carefully this is done, there are unfortunately many snags which may arise and upset the figures. Routes may have to be altered due to wayleave difficulties or Town and Country Planning objections. Spells of bad weather may be encountered during construction which may hold up the job for days or even weeks on end, or excessive rock may be discovered, all of which upset the labour costs and generally show up as overspending on the final job. The country planner's work is often hampered by inter-estate feuds between owners of adjacent

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properties where each landowner tries his best to ensure that towers and poles are placed on the other man's property. This frequently means the selection of an entirely new and often more expensive route.

The type of territory met with in the Borderland can be divided roughly into two categories, the hill-land, much of it over 2 000 ft above sea-level and mostly rough grazing, and the fertile valleys and plateau land which are chiefly agricultural. The techniques for dealing with the two types of country differ greatly. In the hill-land the question of accessibility is of paramount importance, whereas in the arable parts every effort must be made to minimize interference with agriculture by siting overhead line supports in convenient hedges, alongside walls and so on.

The difficulties encountered at the construction stage of a job are many and varied. Valuable time is spent getting men and materials to the job, and if there are several jobs proceeding simultaneously adequate supervision becomes a problem. On the agricultural land, crop damage is an unavoidable expense, and such a simple thing as inadvertently leaving a field gate open can at times give rise to serious damage claims. In country places where there are no convenient metallic water pipes the question of providing a suitable earth connection can prove both difficult and expensive. As the majority of rural schemes are overhead the provision of an aerial earth or of protective multiple earthing is often the only solution. Rivers, particularly where they flow over pebbly soil, sometimes alter their courses at times of spate, or their banks get washed away, and overhead lines in the vicinity frequently need emergency repairs or even re-routing. In an attempt to cheapen the erection costs of rural overhead lines many mechanical devices such as pole-hole boring machines or mechanical shovels have been marketed. Under ideal conditions these machines certainly do what is claimed for them, but when difficult situations arise such as stony ground or bad contours the old-fashioned manual methods would seem to hold their own. At this stage I should like to show you a few more typical hill scenes.

[Here were shown a further nine coloured views of the territory under consideration—mostly on the northern slopes of the Cheviot Hills.]

I think that it is perhaps when we consider the operation and maintenance side of our engineer's work that the special difficulties of the lesser populated territory become most obvious. With the establishment of larger operational units the provision of the necessary standby and transport facilities can be a major problem. Then, as for economic reasons rural distribution is normally by means of overhead lines, we have to contend with the many natural hazards to which these are prone. Lightning, gales, snowstorms and large birds are perhaps the most common, but floods, migratory birds and stock rubbing on stay wires all contribute to the quota of outages. The modern tendency towards the introduction of auto-reclose switches at strategic points in the systems is, however, helping to keep these outages to a minimum.

In order to carry out necessary repairs and maintenance sections of the various distribution networks must from time to time be made dead. With the ever-increasing popularity of electricity it is becoming more and more difficult to arrange those shut-downs without causing inconvenience to some part of the community. From midnight to midnight especially during week days someone is using electricity. In addition to the everyday users there are also a great number of what might be termed seasonal loads. These include such diverse activities as chicken hatching, pig farrowing, grass and grain drying, special shows on radio or television, and of course the annual civic weeks or common ridings held in almost every town in the Borders. A great help in arranging the more awkward shut-downs is the provision of a few small portable petrol-driven generating sets which can be used to maintain the supply to vital pieces of apparatus where an interruption would cause special hardship.

There is one further aspect of an engineer's work in country places that must never be overlooked. The more isolated a community, the more it has to rely on itself for providing its entertainment. A good going staff social club or some such organization catering for the interests of the majority of its members should therefore be encouraged. Such an organization helps to foster good relations between members of the staff and moreover goes a long way towards getting the best results from everybody from the boss down to the youngest apprentice.

DISCUSSION ON
'RESULTS OF FULL-SCALE STABILITY TESTS ON THE BRITISH 132 kV GRID SYSTEM'*
AND
'ORGANIZATION FOR LARGE-SCALE GRID SYSTEM TESTS'†

ore the NORTH STAFFORDSHIRE SUB-CENTRE *at* STAFFORD, 27*th October, the* NORTH-WESTERN CENTRE *at* MANCHESTER, 4*th November*, 1958, *the* SOUTH-WEST SCOTLAND SUB-CENTRE *at* GLASGOW, 21*st January, and the* WESTERN CENTRE *at* CARDIFF, 9*th March*, 1959.

Ir. S. E. Newman (*at Stafford*): The Cliff Quay tests described the papers are, I believe, the most comprehensive full-scale s of their nature so far made on the British Grid system. eir primary purpose was to compare the actual performance h analytical results, and it is reassuring to observe the good eement with transient studies made on conventional network lysers for which the usual simplifying assumptions, menned in Section 2.4, had been made.

The results of the tests with the generator operating underited are of particular interest and show that, even with a ad band' automatic voltage regulator, stable operation was ainable with a rotor angle of some 130°. Subsequent tests other sites have shown similar performance. At Marchwood angle of 129° was recorded.

With the expansion of the Grid system, increasing reactive wer has to be absorbed by the generators under light-load nditions.

n view of the results of the tests, it would be of interest to ow whether the C.E.G.B. are considering the practicability cutting the present safety margins and operating closer to the oretical stability limits of the generators. The alternatives uld appear to be higher short-circuit ratios or the provision of nt reactors.

All the tests made so far have been on steam turbo-alternators, round rotors, but similar tests with a salient-pole waterwheel ernator would be valuable, particularly in relation to the export rket. Could the authors say whether there is any prospect such tests being made? For salient-pole machines the trannt torques may be of a different order from those for roundor alternators.

Mention is made in the paper by Dr. Last and Messrs. Mills l Norris that rotor-angle indication and possibly recording uld be useful. I understand that machine-angle indicators e provided at the Ince power station in the North-West gion. Have these proved useful, and what experience has n gained?

The comparative ease with which synchronism could be ored after the generator had fallen out of step has been firmed in more recent tests; nevertheless, there is a vast erence between controlled tests and normal station operation. The proposed programme included paralleling an unexcited erator and subsequently closing the field circuit. This was carried out at Cliff Quay but has been subsequently done. results of the latter tests would be instructive.

Ir. D. G. Taylor (*at Stafford*): Table 7 of the paper by Dr. emann and Mr. Casson summarizes the effects on stability each of the factors usually neglected in analyser studies. They show that neglect of machine losses, governor, automatic voltage regulation and damping tends to give a pessimistic result, whereas neglect of flux decay tends to give an optimistic result; the overall result is about 5% optimistic.

As governor and automatic-voltage-regulation responses are improved, better automatic control of power systems becomes possible. An example of this is the reduction in the variation of tie-line power which may be brought about by causing one particular generator to take up any departure of the tie-line power from its desired value; this generator is controlled by a governor receiving, as its input, 'tie-line power error' instead of the conventional 'speed error'.

With increasing interconnections between control devices and the power system, it becomes more and more necessary, when carrying out an analyser study, to allow for the effects of the governor and automatic voltage regulator. If an allowance is not also made for the effect of the flux decay, the overall result of the analyser study will tend to become even more optimistic than the 5% quoted by the authors. When departing from the simplified approach, where the positive and negative errors are happily balanced, it is important to know what balance of error remains. Table 7 is of assistance in this assessment.

In Section 5.3.1 it is stated that modified calculations were made allowing for flux decay by using a reduced voltage behind the transient reactance after the fault. It would be of interest to know exactly how these calculations were made. It would also be of interest to know the maximum value reached by the slip ($\Delta\omega/\omega_0$) during the semi-stable oscillations involving pole slipping.

Mr. F. R. L. Creek (*at Manchester*): How does the duration of faults used in the tests compare with the actual fault times to be expected on a system of this nature? This is of interest in determining the performance required from essential auxiliaries, such as the motor-driven exciters which are in use at a few stations, including Cliff Quay. In the case of Cliff Quay the exciters were designed to deliver ceiling excitation for several seconds. In the light of fault times given in the paper by Dr. Busemann and Mr. Casson this period was longer than necessary and justifies a later decision to remove the flywheels provided to increase their inertia constants.

Machines are now under consideration having outputs about eight times greater than the Cliff Quay generators. These can only be constructed within the present limitations of physical size if the ampere-turn loading is substantially increased. This results in high synchronous and transient reactances. It has already been demonstrated in tests at Stella and Castle Donington that, in the steady state, a high synchronous reactance is possible if machines are provided with quick-response regulators, having no dead band. However, the inherently high transient reactance (which may exceed 40% for a generator-transformer combina-

* BUSEMANN, F., and CASSON, W.: Paper No. 2575 S, February, 1958 (see 105 A, 7).
† LAST, F. H., MILLS, E., and NORRIS, N. D.: Paper No. 2559 S, February, 1958 105 A, p. 363).

tion), coupled with lower inertia constants, will increase the danger of transient instability.

Did the authors include in Fig. 8 the additional losses due to induced current in the rotor windings and any estimate of damping-current losses? The rotors in question have non-magnetic low-conductivity wedges which I would expect to increase the depth of penetration. Although the recorded 100 c/s current in the windings is small in tests Nos. 1.2–1.4, a much larger current and loss must occur in the rotor body. The lack of a damper winding and the use of magnetic wedges in the pole slots may account for the variation in reactive-power input noticed in the asynchronous tests.

Mr. F. V. Dakin (*at Manchester*): Has consideration been given to the economics of designing the system to be stable for 3-phase rather than phase-to-phase faults? The severity of the 3-phase faults is much greater but their incidence is very low. Risks have to be taken, for example, on the relatively long protective clearance times, when high-speed protective gear is taken out of commission owing to pilot troubles.

In the interests of transient stability it is essential that the excitation of sets should not fall below certain minimum values, but it is sometimes necessary to ensure that the reactive output of the generators is not too high, otherwise trouble can be experienced, on loss of generation, owing to voltage instability. This occurred on a system recently investigated, which comprised a generating station with five sets and three 33 kV switchboards interconnected by a mesh reactor arrangement. It was coupled to a Grid supply point some three miles away by means of reactors. If the largest generator tripped on fault whilst the station was supplying full reactive output, trouble was experienced owing to low voltage on the 6·6 kV load fed from one of the 33 kV switchboards. This could not be corrected by tap changing. However, if the reactive output of the sets was reduced under normal conditions in conjunction with higher taps on the Grid transformers, no trouble was experienced from voltage instability, since, on tripping the largest set, the remaining sets automatically increased their reactive output owing to the low voltage.

Tests were carried out by one of the switchgear manufacturers to investigate the performance of special relays designed to prevent tripping of circuit-breakers at a phase displacement of 180°. Whilst the switchgear is normally only tested for 1·5 times phase-neutral voltage, this problem has been with us for many years. For example, if a set is required to trip after closing out of synchronism, the same condition applies.

Mr. A. H. Gray (*at Manchester*): It was disappointing to learn of the difficulties experienced by the *micro-réseau* system, which, if it were able to give the requisite accuracy, would be a valuable tool in system studies. I understand that considerable work has been carried out on the system both in France and this country since the tests, and I wonder whether the overall accuracy has been improved.

The modern automatic voltage regulator can be assessed on two characteristics:

(*a*) It can be designed to be continuously active, as with the all-electric regulator; or with a dead band, as with the electro-mechanical regulator.

(*b*) It can be designed so that the overall excitation system has a normal or an extremely high rate of response, bearing in mind that the regulator and excitation system must be regarded as a single unit.

I believe that (*a*) is more important than (*b*), since it contributes to the dynamic stability. (*b*) has little effect on the dynamic stability and can only make an effective contribution to the transient stability when the switching times of the system exceed some half a second.

Unfortunately the tests described by the authors were carried out with dead-band regulators, and it may be of interest th subsequent tests have been carried out on both 60 and 100 M sets. Continuously-active regulators have allowed the machin to operate on full load with a rotor angle approximating to 13 with complete stability.

In effect, this renders the electro-mechanical regulator obs lescent, but experience gained during the last decade appea to justify the step.

Where a high-rate-of-response excitation system is necessar it will be obvious that the exciter capacity must be increase The continuously-active regulator renders control of the machi easier because of the absence of any non-linear functions.

Whilst tests of this nature are costly and difficult to perforr all the results obtained justify the expense and trouble. I sugge that similar tests be carried out at opportune times with th protective system as the main criteria.

Mr. T. R. Warren (*at Glasgow*): Although the primary obje of the tests was to determine the extent to which netwo analysers can be relied upon to simulate actual system pe formance, they were also of value in focusing attention on th importance of carrying out detailed studies to ensure that th generating and transmission systems will do all we ask of the without instability troubles arising. There are several facto which, in the future, will rather militate against satisfacto system operation at times of light load unless proper precautio are taken.

First, the average capacity of new generating stations no being constructed has increased at a greater rate than th system load, with the result that the off-peak load will be m from fewer stations as time goes on. This means that heavi loads will require to be transmitted over longer distances, a system stability margins will be correspondingly reduced. Th effect will be accentuated in England and Wales with the heav concentration of nuclear power plant in the south, which, b the mid 1960's, will, no doubt, be called upon to supply muc the greater part of the system load during the off-peak perio with heavy load transfers from south to north. This may we bring its own stability problems, not to mention high syste voltage at the receiving end. Furthermore, the 275 kV Gr system introduces another difficulty in that the rate of increa in the charging reactive power of circuits with increasing voltag is much greater than the rate of increase in their load-carryir capacity. This difficulty will become even more pronounce should it be necessary, as no doubt it will be, to resort to 275 k cable circuits of appreciable length to reinforce supplies to o large cities.

These questions are all very much in our minds at prese in south Scotland, and calculations have shown that, eve allowing for the improved performance of modern generato steps will have to be taken to compensate on a fairly large sca the charging current of the system during light load period This will not only relieve the duty on the generators, but, b careful selection of the points at which the compensation applied, it is possible to preserve a reasonably normal voltag level everywhere on the transmission systems, both Supergr and Grid systems. This policy is further encouraged by develo ments in the art of compensation, which are at present bei pursued.

Capacitance compensation cannot be expected to provi the complete solution to the stability problem. The Poo tests demonstrated the ability of the magnetic-amplifier ty of voltage regulator to preserve stability with rotor angles we in excess of 90°, and quick-acting regulators must be used o an increasing scale. At the same time it would be unwi to place sole reliance on these regulators to ensure stabilit The authors' views on these questions would be most interestin

studied the papers largely with a view to obtaining some idea the improvement which could be obtained with capacitance npensation in terms of maximum fault-clearance times, but all tests were carried out with the test machine operating at proximately 0·98 lagging power factor, which corresponds re to day-time rather than night-time running conditions. ny was this necessary for a machine having a short-circuit io of 0·6, and to what extent would the test results have been ected under leading-power-factor conditions? The operation the remaining machines even further inside the steady-state bility limit was no doubt considered necessary to avoid pole pping on their part and thus ensure that an adequate synonizing current would be available to pull the test machine o step. In practice, all similar machines in a station are ually working under identical conditions and any tendency vards instability affects them all in equal measure. The rent required to restore synchronism is much greater, and, make matters worse, it has to be supplied from other stations nnected to the system, which, at times of light load, are atively few in number and correspondingly further away.

The results of the Cliff Quay tests are of considerable indirect ue in the assessment of the risks of instability arising under worst conditions in so far as they increased our confidence in work analysers and other devices which have been developed enable synthetic system tests to be carried out.

Mr. K. G. Glover** (*at Cardiff*): In Section 6 of the paper by Last and Messrs. Mills and Norris, it is stated that the tests nonstrated the inadequacy of normal panel instruments and usefulness of a rotor-angle indicator during unstable conons. When a system fault occurs, the operator will not rmally be at the appropriate panel, and so the 'corrective ion' must be made automatically. How should this be done?

Mr. L. W. Campnett (*communicated*): Every indication is given the paper by Dr. Last and Messrs. Mills and Norris that the ganization worked smoothly. Are we to assume that no sigcant changes in the organization of future tests are desirable? ould also like to know the approximate cost of the tests.

One of the conclusions from the tests is that the assumptions de in system studies on the network analyser give acceptable ults in so far as turbo-alternators are concerned. With the ent of high-load-factor nuclear power stations there could nceivably be a case for more pumped-storage schemes, on the es of the Ffestiniog project. Those of us concerned with the nnection of hydro-electric plant have made the appropriate umptions in applying the problem to the network analyser. the authors feel that the different characteristics involved such as to warrant, in due course, a series of tests like those Cliff Quay?

In a closely knit system such as that existing in this country, tability is not a major problem. However, the chances of tability occurring are increased to some extent by the fact that rating staff very rarely have a completed system to operate ng to the almost continuous system development. This state affairs can embarrass operation engineers, and can result in ditions favourable to instability under fault conditions.

therefore agree with the desirability of installing at selected ions rotor-angle indications, and, coupled with this, the irability of adequate training of station operating staff on tters concerning generator instability

Mr. W. Casson (*in reply*): It is with great sorrow that I have reply to this discussion without the help of my esteemed author Dr. Busemann, whose sudden death occurred some nths ago.

In reply to Mr. Newman, the C.E.G.B. are considering the cticability of designing new generators to effect the savings technical advantages that the tests at Cliff Quay and later at Stella have indicated are possible. However, before a decision can be made, an investigation is necessary into the general requirements of the system for voltage levels and reactive power under all conditions of operation.

In reply to Messrs. Newman and Campnett, I understand that tests similar to those at Cliff Quay are being contemplated on salient-pole machines in France, which has a preponderance of these.

The tests on paralleling an unexcited generator and subsequently closing the field circuit were scheduled to be carried out at Cliff Quay, but for special reasons they were not done. However, they were carried out at Stella without any difficulty arising and have been described in a paper.*

In reply to Mr. Taylor, the modified calculations allowing for flux decay simply mean reducing the internal voltages in the power/power-angle calculations.

In reply to Mr. Creek, the durations of faults in the Cliff Quay tests were set to be as near as possible to the time at which the test machine would be just stable, as calculated on the network analyser. These times were much longer than those which would occur with a normal clearance by the feeder protective gear, which would be about 0·3 sec in most cases. The variations in reactive power which were observed during the asynchronous tests are certainly influenced by the presence of a damper and magnetic wedges in the pole slots. Tests carried out on a 30 MW machine some years ago showed that the variations of reactive power and slip with the rotor field winding short-circuited were about twice as great as those with the rotor field winding open-circuited. A solid forged rotor would probably produce no fluctuations at all.

In reply to Mr. Dakin on the incidence of 3-phase faults, there would probably be some gain in designing a system to be fully stable for phase-to-phase and single-phase faults but not for 3-phase faults. This might be worth while doing for a new system but not necessarily for further extensions to an existing system in which the existing machines are designed to give stability on 3-phase faults.

In reply to Mr. Gray, I am unable to say whether the *micro-réseau* system as used in France has yet been modified to improve the overall accuracy, but I agree that this system is, in principle, ideal for system studies. Mr. Gray's remarks on modern automatic voltage regulators are interesting, and I regret that it was not possible to have one in commission at Cliff Quay for the tests. This had been contemplated but it was not possible to obtain a unit in time. I agree that the results of tests like those carried out at Cliff Quay and Stella justify the expense and trouble, and I hope that it will be possible to carry out further tests in the near future on the lines he suggests.

Mr. Warren has given some interesting comments on the problems that will have to be faced in the future in dealing with load flows which occur during off-peak periods. I agree that it would be unwise to place sole reliance on modern regulators to ensure stability, since the possibility of a fault occurring on the regulator with the machine operating on leading power factor must be considered. I think that it will be necessary to carry out further system tests to determine the stability limits on a generator when operating on leading power factor.

I agree with Mr. Glover that there is scope for carrying out 'corrective action' automatically in the event of steady-state instability, but I would not like to indicate here how this should be done.

In reply to Mr. Campnett, it is difficult to arrive at the true cost of the tests at Cliff Quay, i.e. taking all the factors into consideration, but the budgeted cost was about £1 000.

* MASON, T. H., AYLETT, P. D., and BIRCH, F. H.: 'Turbo-Generator Performance under Exceptional Operating Conditions', *Proceedings I.E.E.*, Paper No. 2846 S, January, 1959 (106 A, p. 357).

With regard to the organization, improvements can always be made on subsequent tests, but it would be difficult to improve on the organization of the Cliff Quay tests as described in the paper by Dr. Last and Messrs. Mills and Norris. I agree that it is desirable to train station operating staff on the causes of generator instability and remedial measures, and I believe that lectures have already been given in the London Division on this subject which have been greatly appreciated by the station operating staffs who attended.

Dr. F. H. Last, and **Messrs. E. Mills** and **N. D. Norris** (*in reply*):

Increasing Apparent-Power Demand.—It will be economic to meet some of the increasing reactive-power demand on lightly loaded generators by operating at higher rotor angles. Operation will be nearer the stability limit, but a reduction in the safety margin will be offset by the better performance of modern voltage regulators. The information obtained from indicating rotor-angle instruments during the tests and the useful experience gained on subsequent installations make it evident that they will play an important part in the operation of generators near the stability limit. It is important that each generator should be operated with some reserve of reactive-power capacity.

Fault-Clearance Times.—The fault-clearance times used in the tests were chosen to produce marginal instability and were considerably in excess of the range 0·1–0·2 sec in which most system faults are cleared by the main protective gear. However, the times used were comparable with those which result when the main protective gear is out of commission. On the 275 kV system, standby high-speed protection is used to keep fault-clearance times compatible with stability.

Design for Stability under 3-Phase Fault Conditions.—The use of high-speed protective gear has virtually eliminated the possibility of single-phase faults developing into 3-phase ones. The main risk of a 3-phase fault being left on the system after maintenance will always be present. The condition is particularly dangerous because a 3-phase fault is applied to an already weakened system when a feeder having an accidental 3-phase earth is switched in. It is our opinion that stability conditions should be based on the possibility of a 3-phase fault.

Circuit-Breaker Tripping 180° Out of Phase.—This is a situation that is likely to arise during unstable conditions. It is suggested that the principle of the rotor-angle indicator adapted to a relay function could be used as an interlocking device in the case of generator switches.

Operation of the Station During the Tests.—It is appreciated that, during the tests, Cliff Quay was operated in an abnormal way, the object being to reconcile theory with practice. If the busbars had been coupled, all the sets would have been affected in a similar way and more synchronizing power would have been drawn from the system. As stated in the paper, the tests were staged and the station was operated to produce the minimum risk and disturbance to consumers' supplies. The organization was devised to meet the requirements of the programme, and the organization of subsequent tests will be tailored to meet the different conditions.

Automatic-Voltage-Regulator Performance.—The comments of many speakers on the voltage-regulator performance are appreciated, but such an investigation was outside the scope of the programme. The other steady-state tests, designed to study voltage-regulator performance to which reference has been made, were carried out elsewhere.

Automatic Corrective Action.—Some of the tests showed that during pole-slipping conditions, the conventional governor was admitting steam when the rotor was advancing and vice versa; hence re-synchronism was being hindered. It would appear that steam control partially derived from rotor angle is worth consideration.

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SELECTION OF RELAYING QUANTITIES FOR DIFFERENTIAL FEEDER PROTECTION

By COLIN ADAMSON, M.Sc.(Eng.), Associate Member, and E. A. TALKHAN, B.Sc., Ph.D.

(*The paper was first received* 14*th February, and in revised form* 5*th August*, 1959.)

SUMMARY

ifferential feeder protection, in general, uses a single relaying ntity derived from all phases of the system being protected. The r contains a comprehensive analysis of the nature of this relaying ntity for the whole range of single shunt faults and all likely binations of phase-sequence quantities extracted from the faulted em. The analysis includes the well-established case of the summa- transformer, this device having an output which contains positive, tive and zero phase-sequence components of current. The ysis is presented in the form of curves giving the relaying quantity rms of the important components of the various phase-sequence edances of the power system. From these curves it is possible to pare the different ways of deriving the single-phase relaying ntity and thence to specify the general rules for selection of e-sequence networks.

order to provide a comprehensive method for determining a rential relaying quantity in magnitude and phase, a general chart been developed; from this, the magnitude and phase of the relaying ntity, derived from any specified phase-sequence network, may be ined graphically in terms of the positive and zero phase-sequence tances and the zero-sequence resistance of the power system.

nally, the effect of load current on the magnitude of a derived ying quantity has been considered. The corresponding effect on e has not been treated since it has already appeared elsewhere, ough the results have been included for purposes of comparison completeness.

LIST OF PRINCIPAL SYMBOLS

Z_1 = Positive-phase-sequence reactance and impedance.
Z_0 = Zero-phase-sequence reactance and impedance.
R_0 = Zero-phase-sequence resistance.
I_m = Derived relaying quantity.
I_F = Power system fault current.
a = 120° operator.
M = Real coefficients denoting selected amounts of negative-phase-sequence current.
N = Real coefficient denoting a selected amount of positive-phase-sequence current.
K = Real coefficients denoting selected amounts of zero-phase-sequence current.

(1) INTRODUCTION

ne principle of comparing input with output currents is an one in the history of protection, younger only than the idea traightforward over-current protective arrangements. The ntities at each end of the protective system may be compared ither magnitude or phase, or a combination of both, and main problems include their selection at each end in order nsure that coverage is obtained for all likely faults on the ected system. In order that relaying should be accomplished a single quantity at each end of the system, it is necessary dopt some arrangement of combining the currents from all three phases; the classical way is by means of the summation transformer, which possesses important and well-known limitations. Since the inception of phase-comparison carrier protection in its modern form,[1,2,3] it has been customary to use combinations of symmetrical-component (sequence) quantities for the purpose of comparison. Opinions have differed as to the best combination of sequence quantities. McConnell, Cramer, and Seeley[2] preferred to use the formula $MI_2 + KI_0$, with special provision for 3-phase faults; Harder and Bostwick[4] used a combination of positive and zero sequence currents for pilot-wire relaying; Ellis,[5] discussing phase-comparison carrier protection, has indicated that more recent opinion favoured the combination of I_2 and I_1. A recent paper[6] by the authors has discussed the choice of sequence quantities for a differential protection using a carrier channel and exploiting the transistor; the full argument relating to this choice and a critical comparison of the various possible combinations of sequence quantities have not appeared in protective-gear literature, and it is one of the objects of this paper to present them. Application to feeder protection is the main concern, although the considerations apply equally well to all other forms of differential protection which use a single-phase quantity derived from a 3-phase system. Symmetrical-component analysis has been extended also to the case of the summation transformer, for completeness, and to indicate its relationship to the various sequence networks. In all cases the available output quantity has been plotted against X_0/X_1 or R_0/X_1 in a series of families of curves.

The many variations which can occur in the impedances of an electrical power system make it difficult to determine the magnitude and/or phase of the final relaying quantity in all cases. To facilitate this, a chart has been introduced which enables I_m to be determined directly for a given choice of sequence network in terms of X_0/X_1 and R_0/X_1.

The effect of load current and capacitance charging current on the magnitude and phase of the relaying quantity is of importance. Capacitance currents may be compensated by the introduction of identical currents at the receiving end, or taken into account by appropriate selection of the margin of stability of the protection, and are thus not considered here. The presence of load current requires separate assessment, however, since this may be significant in the event of a high ratio of maximum load current to minimum fault current. Only the effect on the magnitude of the relaying quantity is considered here, since the effect of load current on the phase of the relaying quantity has been analysed in a previous paper.[6]

(2) TYPES OF FAULT

Eleven different shunt faults have to be considered. There are three line-to-earth, three double line-to-earth, three line-to-line and two 3-phase faults, one of them involving earth. The fault current subsequent to any of these faults depends on a multiplicity of factors, such as earthing arrangements, magnitudes and phases of source and line impedances, load impedances

itten contributions on papers published without being read at meetings are d for consideration with a view to publication.
. Adamson and Dr. Talkhan are in the Power Systems Laboratory, Department ctrical Engineering, Manchester College of Science and Technology.

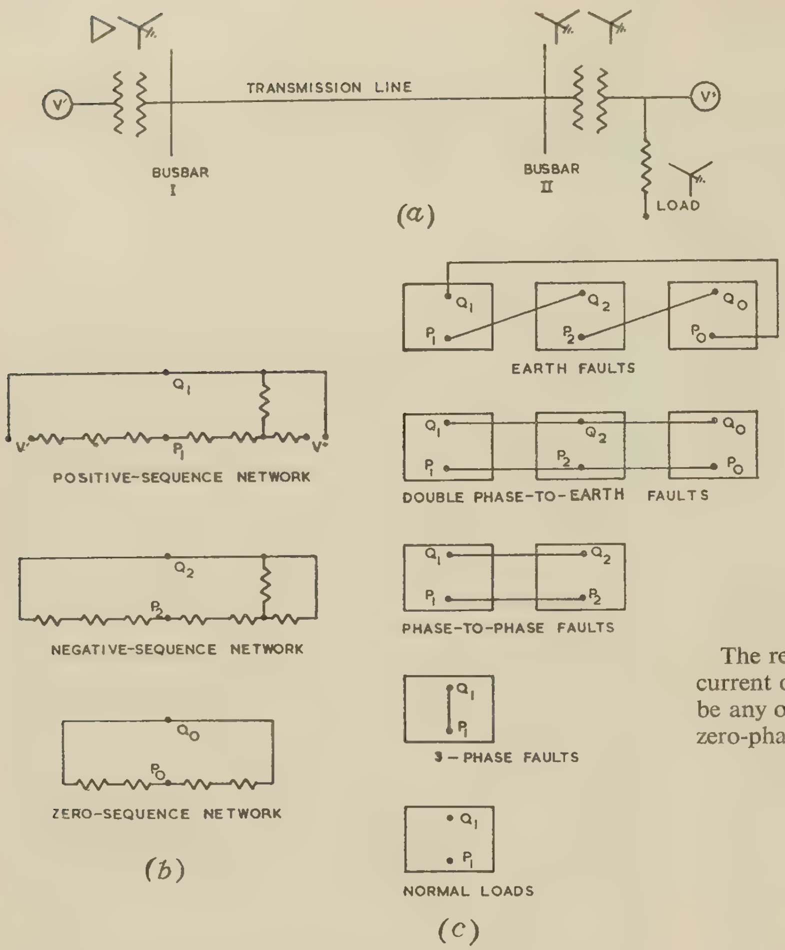


Fig. 1.—Transmission line under various conditions.

(a) Line representation.
(b) Sequence networks.
(c) Sequence network connections for different conditions.

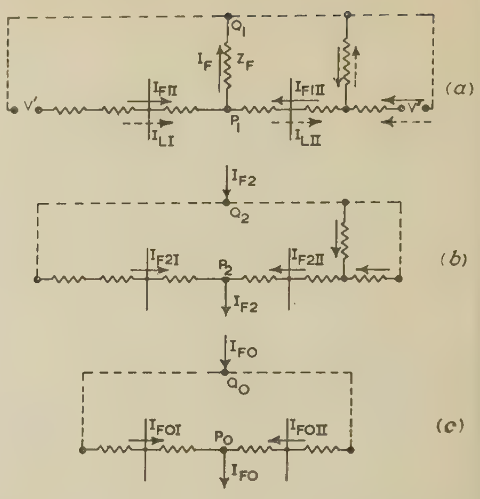


Fig. 2.—Fault current superimposed on load current for system of Fig. 1(a).

(a) Positive phase-sequence current distribution.
(b) Negative phase-sequence current distribution.
(c) Zero-sequence current distribution.

and distribution and fault impedance. In the general appreciation, it is unnecessary to consider all such factors; consideration of the worst and limited conditions will suffice.

The normal method of symmetrical components may be used for studying the system being protected. The sequence-network connections for the different faults, together with the healthy condition, are shown in Fig. 1, from which the impedances shunting the positive phase-sequence network at the point of fault are $(Z_2 + Z_0)$, $Z_2Z_0/(Z_2 + Z_0)$, Z_2, zero and infinity, respectively; the combinations of load and fault currents are shown in Fig. 2.

(3) FAULT-REPRESENTING QUANTITIES

Differential relaying arrangements may be based on phase or amplitude comparison, or a combination of both, of signals derived from each end of the system. All three methods are used in pilot-wire systems; up to the present time only the phase-comparison principle has been used for differential carrier systems. For a 3-phase transmission line with phase currents I_a, I_b and I_c, the symmetrical components of current in phase A are given by the well-known expressions:

$$\left.\begin{aligned} I_1 &= \tfrac{1}{3}(I_a + aI_b + a^2I_c) \\ I_2 &= \tfrac{1}{3}(I_a + a^2I_b + aI_c) \\ I_0 &= \tfrac{1}{3}(I_a + I_b + I_c) \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad (1)$$

The relaying quantity, I_m, which is used to represent the fa current of the 3-phase system in either magnitude or phase, be any of the following functions of the positive-, negative- a zero-phase sequence components of the current in phase A:

$$I_m = NI_1 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad .$$
$$I_m = MI_2 + NI_1 \quad . \quad . \quad . \quad . \quad . \quad .$$
$$I_m = MI_2 + KI_0 \quad . \quad . \quad . \quad . \quad . \quad .$$
$$I_m = KI_0 + NI_1 \quad . \quad . \quad . \quad . \quad . \quad . \quad .$$
$$I_m = AI_2 + BI_0 + NI_1 \quad . \quad . \quad . \quad .$$

where the coefficients A, B, M, N and K may have a range relative values. These combinations may be considered one a time; it is convenient to neglect the zero phase-sequer resistance at first, and then introduce it in order to study effect.

(3.1) $I_m = NI_1$

This positive phase-sequence output is satisfactory only 3-phase faults, and necessitates a choice of high settings for relays; it is thus inadequate for general relaying purposes.

(3.2) $I_m = MI_2 + NI_1$

This combination is commonly held to be the optim combination of phase-sequence quantities for adequate rep sentation of the fault current under all system fault conditio Furthermore, general experience indicates that there should a greater proportion of negative-to-positive phase-seque current in the resulting output. Although the discussion follow is general, the values finally adopted for M and N restricted to $N = \pm 1$ and $M > 1$.

It is necessary to establish the optimum values of M and with regard to their effect on I_m under different fault conditic the possible range of phase-sequence impedances and ld current all being taken into account.

Substituting from eqns. (1) into eqn. (3), it follows that

$$I_m = \tfrac{1}{3}\left\{(M + N)I_a - \left[\frac{(M + N)}{2} + j\frac{(\sqrt{3})(M - N)}{2}\right]I_b - \left[\frac{(M + N)}{2} - j\frac{(\sqrt{3})(M - N)}{2}\right]I_c\right\}$$

1) Single-Phase-to-Earth Faults.

Phase A to earth.

$$I_a = I_F \text{ and } I_b = I_c = 0$$

ubstitution in eqn. (7) gives

$$I_m = \frac{(M+N)}{3} I_a$$

erefore
$$\left|\frac{I_m}{I_F}\right| = \frac{(M+N)}{3} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (8)$$

Phase B to earth.

$$I_b = I_F \text{ and } I_a = I_c = 0$$

ubstitution in eqn. (7) gives

$$I_m = -\frac{1}{3}\left[\frac{(M+N)}{2} + j\frac{(\sqrt{3})(M-N)}{2}\right] I_b$$

erefore
$$\left|\frac{I_m}{I_F}\right| = \tfrac{1}{3}\sqrt{(M^2 - MN + N^2)} \quad . \quad . \quad . \quad (9)$$

Phase C to earth.

his gives the result expressed in eqn. (9) above.

2) 3-Phase Faults.

$$|I_a| = |I_b| = |I_c| = |I_F| = |I_1|$$

$$I_2 = 0$$

erefore
$$I_m = NI_1$$

$$\left|\frac{I_m}{I_F}\right| = N \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (10)$$

3) Double Phase-to-Earth Faults.

Phase B–C–earth ($I_a = 0$).

his fault is represented in Fig. 3, where (*a*) represents the on the 3-phase line, (*b*) shows the connection of the sequence orks and (*c*) represents the conventional schematic equiva- of (*b*). So that the result obtained shall be generally icable, fault impedances Z_F and Z_G are assumed as shown ig. 3(*a*).

eferring to Fig. 3(*c*),

$$\left.\begin{aligned}
I_1 &= \frac{V(Z_2 + Z_0)}{Z_1Z_2 + Z_0(Z_1 + Z_2)} = k(Z_2 + Z_0) \\
I_2 &= \frac{-VZ_0}{Z_1Z_2 + Z_0(Z_1 + Z_2)} = -kZ_0 \\
I_0 &= \frac{-VZ_2}{Z_1Z_2 + Z_0(Z_1 + Z_2)} = -kZ_2
\end{aligned}\right\} \quad . \quad (11)$$

s
$$\begin{aligned} I_m &= MI_2 + NI_1 \\ &= -k[(M-N)Z_0 - NZ_2] \quad . \quad . \quad . \quad (12) \end{aligned}$$

$$\begin{aligned} I_b &= I_0 + a^2I_1 + aI_2 \\ &= k'[(\sqrt{3})Z_2 + j(2Z_0 + Z_2)] \quad . \quad . \quad . \quad (13) \end{aligned}$$

$$\begin{aligned} I_c &= I_0 + aI_1 + a^2I_2 \\ &= k'[(\sqrt{3})Z_2 - j(2Z_0 + Z_2)] \quad . \quad . \quad . \quad (14) \end{aligned}$$

e
$$k' = -\frac{\sqrt{3}}{2}k$$

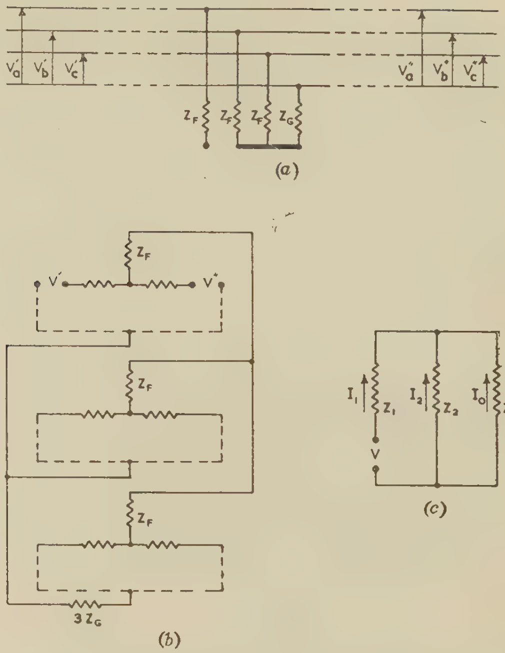


Fig. 3.—Double phase-to-earth fault.

(*a*) Faulted transmission system.
(*b*) Connection of sequence networks.
(*c*) Reduction of Fig. 3(*b*).

Considering either I_b or I_c to be equal to the fault current, the ratio $|I_m|:|I_F|$ is given by

$$\left|\frac{I_m}{I_F}\right| = \frac{2[(M-N)Z_0 - NZ_2]}{\sqrt{3}[(\sqrt{3})Z_2 \pm j(2Z_0 + Z_2)]} \quad . \quad . \quad . \quad (15)$$

Although eqn. (15) can be solved for any values of impedances, including Z_F and Z_G, it will be assumed initially that $Z_1 = Z_2 = jX_1$ and $Z_0 = jX_0$. The first assumption is justified in most practical cases, but the second is not so, since Z_0 may have a considerable resistive component, R_0. It is convenient, however, to introduce R_0 later. Eqns. (11)–(15) thus become

$$\left.\begin{aligned} I_1 &= jk(X_1 + X_0) \\ I_2 &= -jkX_0 \\ I_0 &= -jkX_1 \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad (11a)$$

$$I_b = j\frac{(\sqrt{3})k}{2}[(\sqrt{3})X_1 + j(2X_0 + X_1)] \quad . \quad (13a)$$

$$I_c = j\frac{(\sqrt{3})k}{2}[(\sqrt{3})X_1 - j(2X_0 + X_1)] \quad . \quad (14a)$$

whence

$$|I_F| = |I_b| = |I_c| = (\sqrt{3})k\sqrt{(X_1^2 + X_0X_1 + X_0^2)} \quad (16)$$

and
$$\left|\frac{I_m}{I_F}\right| = \frac{(M-N)\left|\frac{X_0}{X_1}\right| - N}{\sqrt{3}\sqrt{\left(1 + \frac{X_0}{X_1} + \left|\frac{X_0}{X_1}\right|^2\right)}} \quad . \quad . \quad (15a)$$

For $X_0/X_1 = \infty$, which corresponds to double phase faults not involving earth, eqn. (15*a*) becomes

$$\left|\frac{I_m}{I_F}\right| = \frac{(M-N)}{\sqrt{3}} \quad . \quad . \quad . \quad . \quad . \quad . \quad (15b)$$

It is clear from eqn. (11*a*) that I_2 and I_0 are co-phasal and both in phase opposition to I_1.

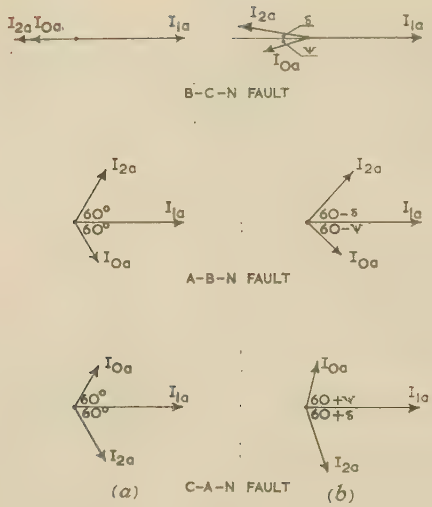


Fig. 4.—Relative phase displacements of the phase-sequence components of the fault current.

$X_0/X_1 = 1 \cdot 33$
(a) $R_0 = 0$.
(b) $R_0 \neq 0$.

(b) Phase A–B–earth and phase C–A–earth faults.

Because of the symmetry of the transmission line, it can be shown that I_2 leads I_1 by 60° and I_0 lags behind I_1 by 60° for A–B–N faults, and I_2 lags behind I_1 by 60° and I_0 leads I_1 by 60° for C–A–N faults; this is illustrated in Figs. 4(*a*) and (*b*) for $R_0 = 0$ and $R_0 \neq 0$, respectively. The magnitudes of I_1, I_2 and I_0 are still given by eqns. (11) and (11*a*), and the magnitude of the fault current is also the same as that given by eqn. (16). It follows that

$$\left|\frac{I_m}{I_F}\right| = \frac{\sqrt{(M^2I_2^2 + N^2I_1^2 + 2MNI_1I_2\cos 60)}}{(\sqrt{3})k\sqrt{(X_1^2 + X_1X_0 + X_0^2)}}$$

$$= \frac{\sqrt{\left[N^2 + (2N^2 + MN)\frac{X_0}{X_1} + (M^2 + N^2 + MN)\left(\frac{X_0}{X_1}\right)^2\right]}}{\sqrt{3}\sqrt{\left[1 + \frac{X_0}{X_1} + \left(\frac{X_0}{X_1}\right)^2\right]}} \quad . \quad . \quad . \quad . \quad (17)$$

(3.2.4) Double Phase Faults not Involving Earth.

The results for these cases may be obtained from eqns. (15*a*) and (17) for the conditions $X_0/X_1 = \infty$. Thus, for the phase B–C fault, from eqn. (15*a*),

$$\left|\frac{I_m}{I_F}\right| = \frac{(M - N)}{\sqrt{3}} \quad . \quad . \quad . \quad . \quad . \quad (15b)$$

For the phase C–A or A–B fault, from eqn. (17),

$$\left|\frac{I_m}{I_F}\right| = \frac{1}{\sqrt{3}}\sqrt{(M^2 + MN + N^2)} \quad . \quad . \quad . \quad (17a)$$

(3.2.5) Effect of Varying *M* in Magnitude and *N* in Sign.

Tables 1 and 2 show the variation in the ratio $|I_m/I_F|$ for changes in M and for $N = +1$ and -1, respectively, for the cases of single phase-to-earth faults and phase-to-phase faults. It is clear that none of the values chosen for M are prohibitive and that either sign may be chosen for N, since $|I_m/I_F|$ is never zero or negative. The higher the value of M, i.e. the greater the proportion of negative phase-sequence current, the higher becomes the ratio $|I_m/I_F|$. This is not the case with double phase-to-earth faults, the results of which are plotted in Fig. 5

Table 1

RATIO $\left|\frac{I_m}{I_F}\right|$ FOR $N = +1$

M	Single phase-to-earth faults		Phase-to-phase faults	
	Phase A to earth	Phase B to earth or phase C to earth	B–C	A–B or C–A
2	1	0·578	0·577	1·527
4	1·67	1·2	1·732	2·645
6	2·33	1·855	2·88	3·782
8	3·0	2·52	4·04	4·93
10	3·67	3·18	5·19	6·08

Table 2

RATIO $\left|\frac{I_m}{I_F}\right|$ FOR $N = -1$

M	Single phase-to-earth faults		Phase-to-phase faults	
	Phase A to earth	Phase B to earth or phase C to earth	B–C	A–B or C–A
2	0·33	0·88	1·732	1
4	1	1·525	2·88	2·08
6	1·67	2·185	4·04	3·215
8	2·33	2·845	5·19	4·355
10	3·0	3·5	6·35	5·5

(full lines) from eqns. (15*a*) and (17). Referring to Fig. 5(it is clear that, for the case of the phase B–C–earth fault a for $N = +1$, $|I_m/I_F|$ passes through zero and becomes negat for real values of X_0/X_1; for $N = -1$, however, there is minimum positive value for $|I_m/I_F|$ in all cases. $N = +1$ thus impermissible, and M must be chosen with regard to t effect of load current on I_m during minimum fault conditio (usually earth faults) and considerations of minimum re settings.

(3.2.6) Effect of Zero-Phase-Sequence Resistance, R_0.

The effect of R_0 can be considered by substituting $R_0 + j$ for Z_0 in eqn. (11), whence

$$\left.\begin{aligned} I_1 &= jk(X_1 + X_0 - jR_0) \\ I_2 &= -jk(X_0 - jR_0) \\ I_0 &= -jkX_1 \end{aligned}\right\} \quad . \quad . \quad . \quad (1$$

It is clear from eqns. (11*a*) and (11*b*) that, due to R_0, I_2 la from its original phase relation with respect to I_1 by an angl equal to $\left[\arctan\left(\frac{R_0}{X_0}\right) - \arctan\left(\frac{R_0}{X_0 + X_1}\right)\right]$, while I_0 lea by an angle ψ equal to $\left[\arctan\left(\frac{R_0}{X_0 + X_1}\right)\right]$. For pha A–B– and C–A–earth faults the phase angles of I_2 and I_0 w respect to I_1 will be reduced and increased, respectively, angles δ and ψ from their original 60° phase relationsh These effects are illustrated in Fig. 4(*b*).

The expression for $|I_m/I_F|$ can be obtained as before; e.g. phase B–C–earth faults,

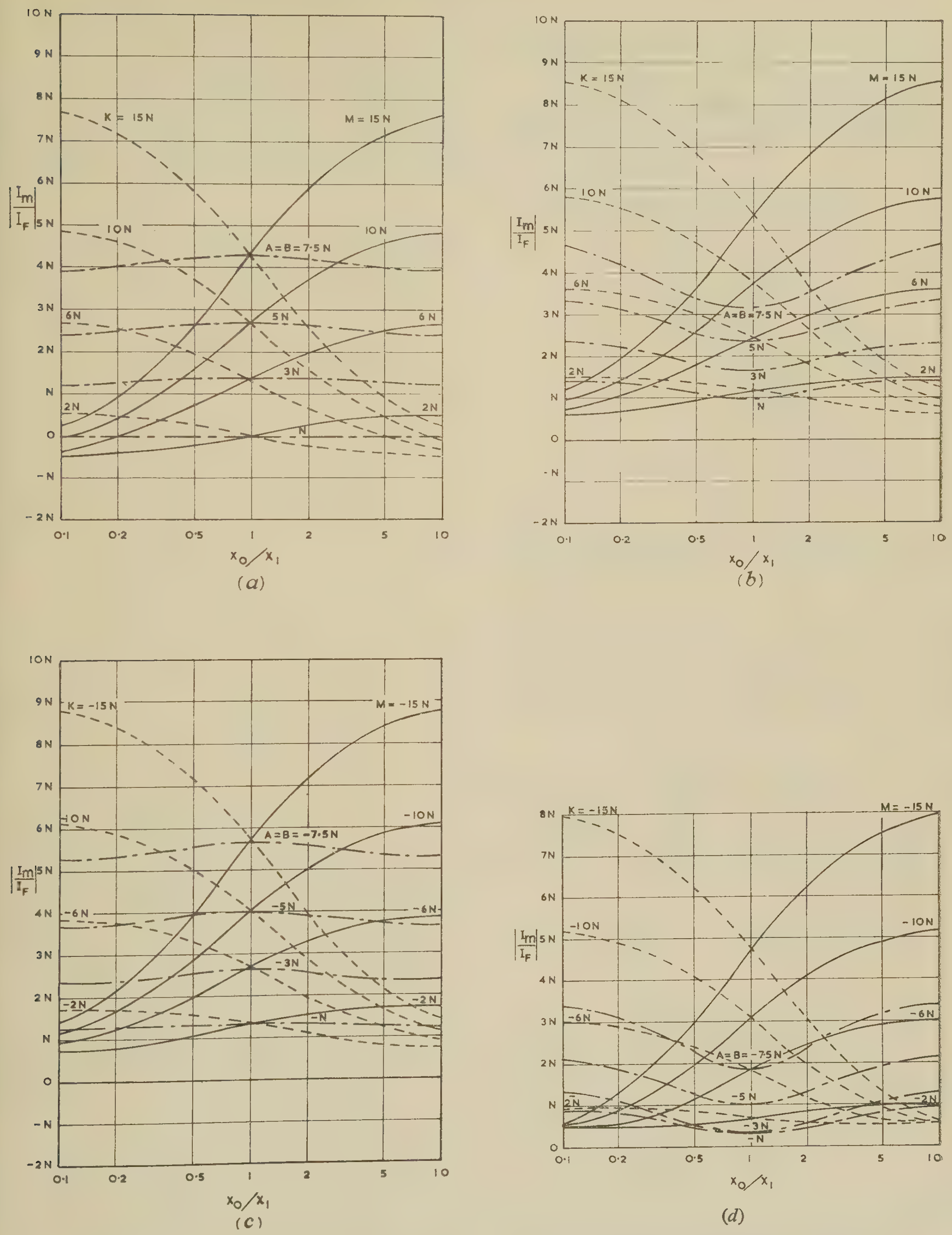


Fig. 5.—Relaying outputs from positive-and-negative, positive-and-zero and positive-and-negative-and-zero sequence networks.

(a) Phase B–C–earth fault.
(b) Phase A–B–earth or phase C–A–earth fault.
(c) Reversed phase of the positive phase-sequence current component: phase B–C–earth fault.
(d) Reversed phase of the positive phase-sequence current component: phase A–B–earth or phase C–A–earth fault.

$$\left|\frac{I_m}{I_F}\right| = \frac{\sqrt{\left[(M-N)\dfrac{X_0}{X_1} - N^2 + (M-N)^2\left(\dfrac{R_0}{X_1}\right)^2\right]}}{\sqrt{3}\sqrt{\left[1 + \dfrac{X_0}{X_1} + \left(\dfrac{X_0}{X_1}\right)^2 + \left(\dfrac{R_0}{X_1}\right)^2 + 3\dfrac{R_0}{X_1}\right]}} \quad (18)$$

The relationship between $|I_m/I_F|$ and R_0/X_1, from eqn. (18), is plotted in Fig. 6 for $N = -1$, $M = 6$ and 3 values of X_0/X_1.

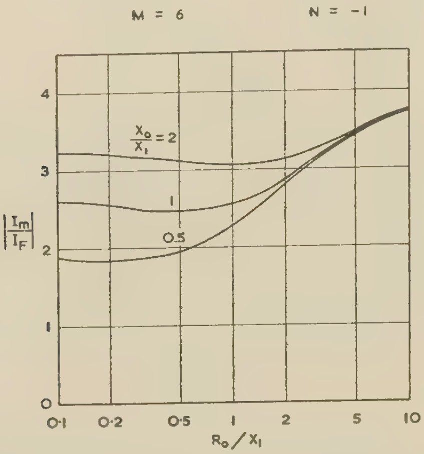


Fig. 6.—Variation in output of the positive-and-negative phase-sequence current network, as a function of R_0/X_1, for the case of phase B–C–earth fault.
$M = 6.$ $N = -1.$

It may be seen that, apart from a slight initial decrease, $|I_m/I_F|$ increases with R_0/X_1. For each value of M, all the curves, for different values of X_0/X_1, approach the same maximum at $R_0/X_1 = \infty$. A similar result may be anticipated for phases A and B- and phases C and A-to-earth faults.

(3.3) $I_m = MI_2 + KI_0$

This combination has been favoured by McConnell, Cramer and Seeley[2] for phase-comparison carrier relaying; they have also produced an analysis justifying this particular choice, but not in a convenient general form. Following the same procedure as in Section 3.2, and neglecting R_0 initially, the expression for $|I_m/I_F|$ for different faults are:

Phase A-to-earth,

$$\left|\frac{I_m}{I_F}\right| = \frac{M+K}{3} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (19)$$

Phase B- (or C) to-earth,

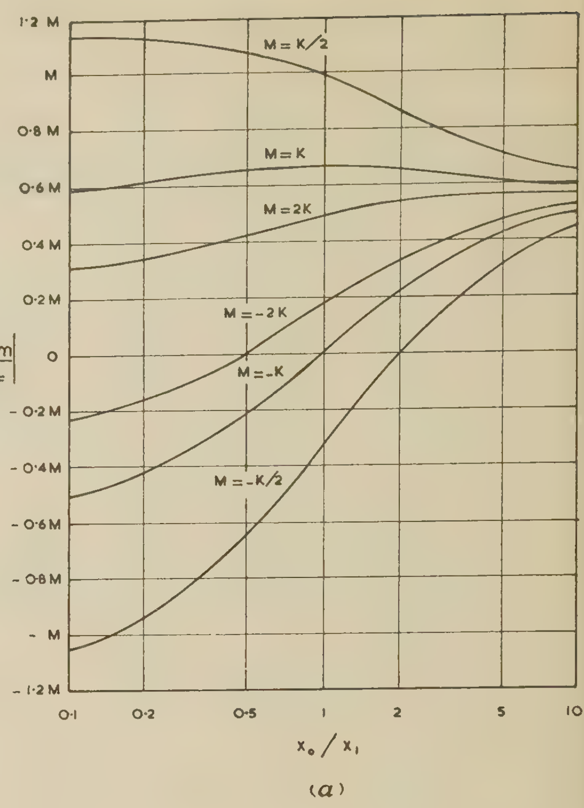
$$\left|\frac{I_m}{I_F}\right| = \frac{\sqrt{(K^2 - KM + M^2)}}{3} \quad . \quad . \quad . \quad (20)$$

Phase B–C–earth,

$$\left|\frac{I_m}{I_F}\right| = \frac{M(X_0/X_1) + K}{\sqrt{3}\sqrt{\left[1 + \dfrac{X_0}{X_1} + \left(\dfrac{X_0}{X_1}\right)^2\right]}} \quad . \quad . \quad (21)$$

Phase A–B (or C–A)–earth,

$$\left|\frac{I_m}{I_F}\right| = \frac{\sqrt{\left[K^2 - MK\left(\dfrac{X_0}{X_1}\right) + M^2\left(\dfrac{X_0}{X_1}\right)^2\right]}}{\sqrt{3}\sqrt{\left[1 + \left(\dfrac{X_0}{X_1}\right) + \left(\dfrac{X_0}{X_1}\right)^2\right]}} \quad (22)$$



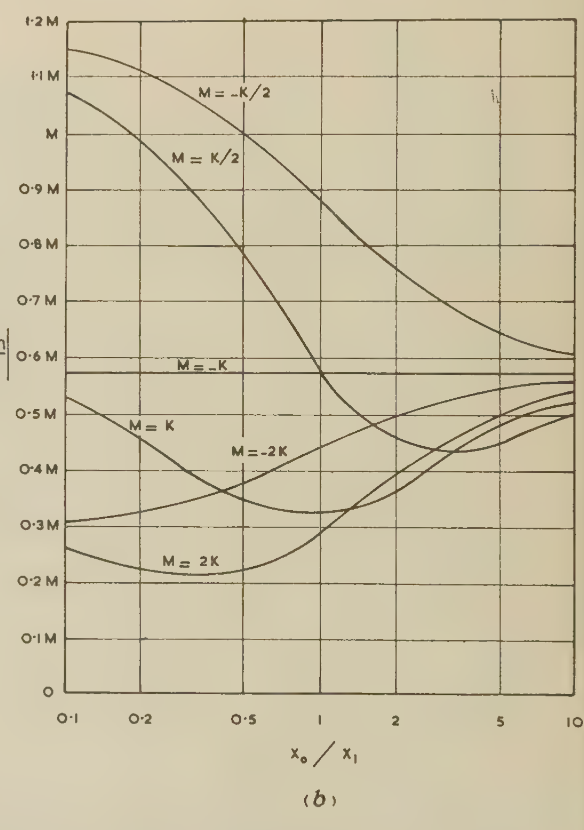


Fig. 7.—Relaying outputs from negative-and-zero phase-sequence networks.

(a) Phase B–C–earth fault.
(b) Phase A–B–earth or phase C–A–earth fault.

qns. (19) and (20) are similar to eqns. (8) and (9), with K acing N. The curves of $|I_m/I_F|$, from eqns. (21) and (22), given in Fig. 7 for $M = \pm K/2$, $M = \pm K$ and $M = \pm 2K$. s particular function has the drawback that special arrange-its must be adopted for 3-phase faults,[2] since normally there o output under these conditions; it will be noted that negative es of M (or K) are impermissible, since the values of $|I_m/I_F|$, his case, for earth and phase B–C–earth faults, pass through . Difficulty is also experienced if R_0 is present, as considered ection 4.

(3.4) $I_m = KI_0 + NI_1$

gain following the same procedure and neglecting R_0 ially, the following expressions for $|I_m/I_F|$ are obtained:

hase A to earth:

$$\left|\frac{I_m}{I_F}\right| = \frac{K + N}{3} \quad . \quad . \quad . \quad . \quad . \quad (23)$$

hase B (or C) to earth:

$$\left|\frac{I_m}{I_F}\right| = \frac{\sqrt{(K^2 - KN + N^2)}}{3} \quad . \quad . \quad . \quad . \quad . \quad (24)$$

hase B–C–earth:

$$\left|\frac{I_m}{I_F}\right| = \frac{(K - N)\left(\frac{X_1}{X_0}\right) - N}{\sqrt{3}\sqrt{\left[1 + \frac{X_1}{X_0} + \left(\frac{X_1}{X_0}\right)^2\right]}} \quad . \quad . \quad . \quad . \quad . \quad (25)$$

hase A and B (or C and A) to earth:

$$\left|\frac{I_m}{I_F}\right| = \frac{\sqrt{\left[N^2 + (KN + 2N^2)\left(\frac{X_1}{X_0}\right) + (K^2 + KN + N^2\left(\frac{X_1}{X_0}\right)^2\right]}}{\sqrt{3}\sqrt{\left[1 + \frac{X_1}{X_0} + \left(\frac{X_1}{X_0}\right)^2\right]}} \quad . \quad . \quad . \quad . \quad . \quad (26)$$

qns. (23) and (24) have the same form as eqns. (8) and (9) h K replacing M. Eqns. (25) and (26) are similar in form to s. (15*a*) and (17), respectively, except that K replaces M and X_0 replaces X_0/X_1. $|I_m/I_F|$, from eqn. (25), is plotted in s. 5(*a*) and (*c*) (dotted lines) for the cases of $N = +1$ and , respectively. $|I_m/I_F|$ for phase A–B (or C–A)–earth faults hown in Figs. 5(*b*) and (*d*) (dotted lines) for the cases of $= +1$ and -1, respectively. The dotted lines of Fig. 5 are images of the full-line curves representing the case $I_m =$ $_2 + NI_1$; from a comparison of the two sets of curves, it be seen that $|I_m/I_F|$ is lower for the higher values of X_1 (a likely situation in practice) for the case $I_m = KI_0 + NI_1$, thus the combination of negative and positive phase-sequence rents is preferable; furthermore, I_0 is zero for phase faults involving earth.

(3.5) $I_m = AI_2 + BI_0 + NI_2$

.1) **Phase-Sequence Network.**

he nature of this output may be obtained by addition of the ctions for I_m of Sections 3.2 and 3.4, i.e.

$$2I_m = MI_2 + NI_1 + KI_0 + NI_1$$
$$I_m = AI_2 + BI_0 + NI_1$$

ere $A = \frac{1}{2}M$ and $B = \frac{1}{2}K$.

For $A = B$, it may be seen from Fig. 5 (chain-dotted lines) that an approximately constant value of I_m/I_F is obtained for phase B–C–earth faults, for all values of X_0/X_1, which is generally desirable. A difficulty arises, however, for the cases of phases A–B– and C–A–earth faults; the functions $I_m = MI_2 + NI_1$ and $I_m = KI_0 + NI_1$ are not now in phase, and their sum may be zero or very low, especially when R_0 is considered.

(3.5.2) **Summation Transformer.**

A 4-winding summation transformer is shown in Fig. 8; the output of the transformer is clearly a function of the positive,

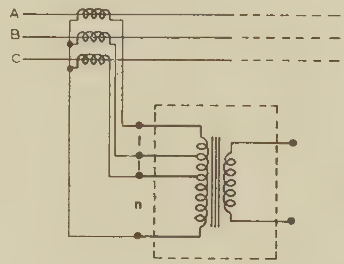


Fig. 8.—Summation transformer connections.

negative and zero sequence components of fault current, the values of A, B and N being determined by the primary turns which are generally n, $n+1$ and $n+2$.

(*a*) *Phase B–C-earth.*

From Figs. 3 and 8, the currents through the four primary terminals of the transformer for this fault are

$$\left.\begin{aligned} I_a &= 0 \\ I_b &= -\frac{(\sqrt{3})k}{2}[(\sqrt{3})Z_2 + j(2Z_0 + Z_2)] \\ I_c &= -\frac{(\sqrt{3})k}{2}[(\sqrt{3})Z_2 - j(2Z_0 + Z_2)] \\ I_n &= I_b + I_c \\ &= -\frac{(\sqrt{3})k}{2}[2(\sqrt{3})Z_2] \end{aligned}\right\} \quad . \quad (27)$$

where k is a constant.

The output current from the summation transformer is

$$I_m \propto I_b + nI_n$$
$$= -\frac{(\sqrt{3})k}{2}[(\sqrt{3})(1 + 2n)Z_2 + j(2Z_0 + Z_2)] \quad . \quad (28)$$

Considering two particular limiting cases of zero phase-sequence impedance, i.e. $Z_0 = jX_0$, and $Z_0 = R_0$, and assuming that $Z_2 = Z_1 = jX_1$, then, from eqn. (28), the output from summation transformer is

$$I_m \propto -j\frac{(\sqrt{3})k}{2}[(\sqrt{3})(1 + 2n)X_1 + j(2X_0 + X_1)]$$

Taking as a convenient reference the output current, I_s, from the summation transformer when the fault current from one phase only flows in one turn on the primary side,

$$I_s \propto -j\frac{(\sqrt{3})k}{2}[3X_1 + j(2X_0 + X_1)]$$

whence, for the case $Z_0 = jX_0$,

$$\left|\frac{I_m}{I_s}\right| = \frac{\sqrt{[(1 + 3n + 3n^2) + X_0/X_1 + (X_0/X_1)^2]}}{\sqrt{[1 + X_0/X_1 + (X_0/X_1)^2]}} \quad (29)$$

and, for the case $Z_0 = R_0$,

$$\left|\frac{I_m}{I_s}\right| = \frac{\sqrt{[1 + 3n + 3n^2) + (\sqrt{3})(1 + 2n)\, R_0/X_1 + (R_0/X_1)^2]}}{\sqrt{\left[1 \pm (\sqrt{3})\frac{R_0}{X_1} + (R_0/X_1)^2\right]}} \quad . \quad . \quad . \quad . \quad (30)$$

Eqns. (29) and (30) are plotted in Fig. 9(*a*) (i) and (ii) respectively.

(*b*) *Phase C–A–earth.*

Using similar reasoning, for the case $Z_0 = jX_0$,

$$\left|\frac{I_m}{I_s}\right| = \frac{\sqrt{\left[(4 + 6n + 3n^2) + 4\frac{X_0}{X_1} + 4\left(\frac{X_0}{X_1}\right)^2\right]}}{\sqrt{\left[1 + \frac{X_0}{X_1} + \left(\frac{X_0}{X_1}\right)^2\right]}} \quad (31)$$

and for $Z_0 = R_0$,

$$\left|\frac{I_m}{I_s}\right| = \frac{\sqrt{\left[(4 + 6n + 3n^2) - 4(\sqrt{3})(1 + n)\frac{R_0}{X_1} + 4\left(\frac{R_0}{X_1}\right)^2\right]}}{\sqrt{\left[1 \pm \sqrt{3}\frac{R_0}{X_1} + \left(\frac{R_0}{X_1}\right)^2\right]}} \quad . \quad . \quad . \quad . \quad (32)$$

Eqns. (31) and (32) are plotted in Fig. 9(*b*) (i) and (ii), respectively.

(*c*) *Phase A–B–earth.*

For the case $Z_0 = jX_0$,

$$\left|\frac{I_m}{I_s}\right| = \frac{\sqrt{\left[(3n^2 + 9n + 7) + 4\frac{X_0}{X_1} + 4\left(\frac{X_0}{X_1}\right)^2\right]}}{\sqrt{\left[1 + \frac{X_0}{X_1} + \left(\frac{X_0}{X_1}\right)^2\right]}} \quad . \quad (33)$$

For the case $Z_0 = R_0$,

$$\left|\frac{I_m}{I_s}\right| = \frac{\sqrt{\left[3n^2 + 9n + 7) + (\sqrt{3})(2n + 3)\frac{R_0}{X_1} + 4\left(\frac{R_0}{X_1}\right)^2\right]}}{\sqrt{\left[1 \pm (\sqrt{3})\frac{R_0}{X} + \left(\frac{R_0}{X_1}\right)^2\right]}} \quad (34)$$

Eqns. (33) and (34) are plotted in Figs. 9(*c*) (i) and (ii) respectively.

Comparison of Figs. 9(*a*)–(*c*) shows the relative outputs from the summation transformer for faults on the different phases. From Fig. 9(*b*) (full lines) it can be seen that there are limiting conditions and that minimum output occurs for $R_0/X_1 \simeq 3$ when $n = 3$; the value of R_0/X_1 for minimum output rises as n increases, the value of the minimum remaining the same for all conditions.

For the case of phase C–A–earth faults, it should be noted that the situation does not improve appreciably for realistic values of $Z_0 = R + jX_1$. The expression for output now becomes

$$\left|\frac{I_m}{I_s}\right| = \frac{\sqrt{\left[(12 + 6n + 3n^2) - 4(\sqrt{3})(1 - n)\frac{R_0}{X_1} + 4\left(\frac{R_0}{X_1}\right)^2\right]}}{\sqrt{\left[3 - (\sqrt{3})\frac{R_0}{X_1} + \left(\frac{R_0}{X_1}\right)^2\right]}} \quad (31a)$$

The dotted curves of Fig. 9(*b*) are for the case of $Z_0 = R_0 + jX_1$; the value of R_0/X_1 for minimum output again depends on the value of n, but the minimum values are only slightly greater than for the case of $Z_0 = R_0 + j0$. It is necessary, because of the poor performance with this type of fault, to assess the system parameters carefully before applying the summation transformer. In general, whatever the turns ratios chosen for the summation transformer, one of the possible combinations of double phase-to-earth faults gives a low per-unit output for the higher values of R_0/X_1. For example, if the turns on the primary side are $1 : m : n$, where $m \geqslant 1$ and $X_0 = X_1$, the minimum value of output for $m = 1$ is 0·5 per unit and occurs at $R_0/X_1 \simeq 6$; the corresponding minima for $m = 3$ and $m =$ occur at $R_0/X_1 \simeq 3{\cdot}75$ and 3·2, and have values which are 2· and 3·3 times greater. Expressed another way, for the phase C–A–earth fault, the variation between maximum and minimum values of relaying output becomes less the higher the value chosen for m, n being constant. On the other hand, if $X_0 =$ an increase in the value of m has little effect on the minimum values, the minimum occurring at lower values of R_0/X_1 the higher the value of m; these results are much the same as that obtained for the $1 : 1 : n$ transformer when the value of is reduced.

(4) GENERAL CHART FOR EVALUATION OF I_m FOR ANY COMBINATION OF SYMMETRICAL-COMPONENT CURRENTS

The multiplicity of curves plotted in Figs. 5–7 may be avoided in practice by the use of the chart shown in Fig. 10; here, current components are represented in terms of R_0, X_0 and X_1. As an example, taking the case of double phase-to-earth faults, and allowing for R_0, then from eqns. 11(*b*) and the corresponding expression for $|I_F|$,

$$\left.\begin{aligned} I_1 &= jk(X_1 + X_0 - jR_0) \\ &\propto 1 + \frac{X_0}{X_1} - j\frac{R_0}{X_1} \\ I_2 &= -jk(X_0 - jR_0) \\ &\propto -\left(\frac{X_0}{X_1} - j\frac{R_0}{X_1}\right) \\ I_0 &= -jkX_1 \\ &\propto -1 \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad (35)$$

and

$$|I_F| = (\sqrt{3})k\sqrt{[X_1^2 + X_0X_1 + X_0^2 + R_0^2 + (\sqrt{3})R_0X_1]}$$

$$\text{i.e. } |I_F| \propto (\sqrt{3})\sqrt{\left[1 + \frac{X_0}{X_1} + \left(\frac{X_0}{X_1}\right)^2 + \left(\frac{R_0}{X_1}\right)^2 + (\sqrt{3})\frac{R_0}{X_1}\right]} \quad (36)$$

Referring to Fig. 10, it will be seen that the axes of the chart are X_0/X_1 in the horizontal direction and R_0/X_1 in the vertical direction. Taking the numerical values $M = K = 6$, $N = \pm$ and $X_0 = R_0 = 2X_1$, then, for the example taken above, from eqns. (35), I_0 is represented by the unit vector OA in the negative X_0/X_1 axis; I_2 is represented by vector $OB = -(X_0/X_1 - jR_0/X_1)$ and I_1 by vector $OC = (1 + X_0/X_1 - jR_0/X_1)$. The concentric circles, with their centre at the origin O, represent the coefficient K of I_0 directly; the same value for the coefficient M is represented by drawing a line parallel to AB from the point E, which is the intersection of the circle with the I_0 vector, to meet the I_2 vector at F.

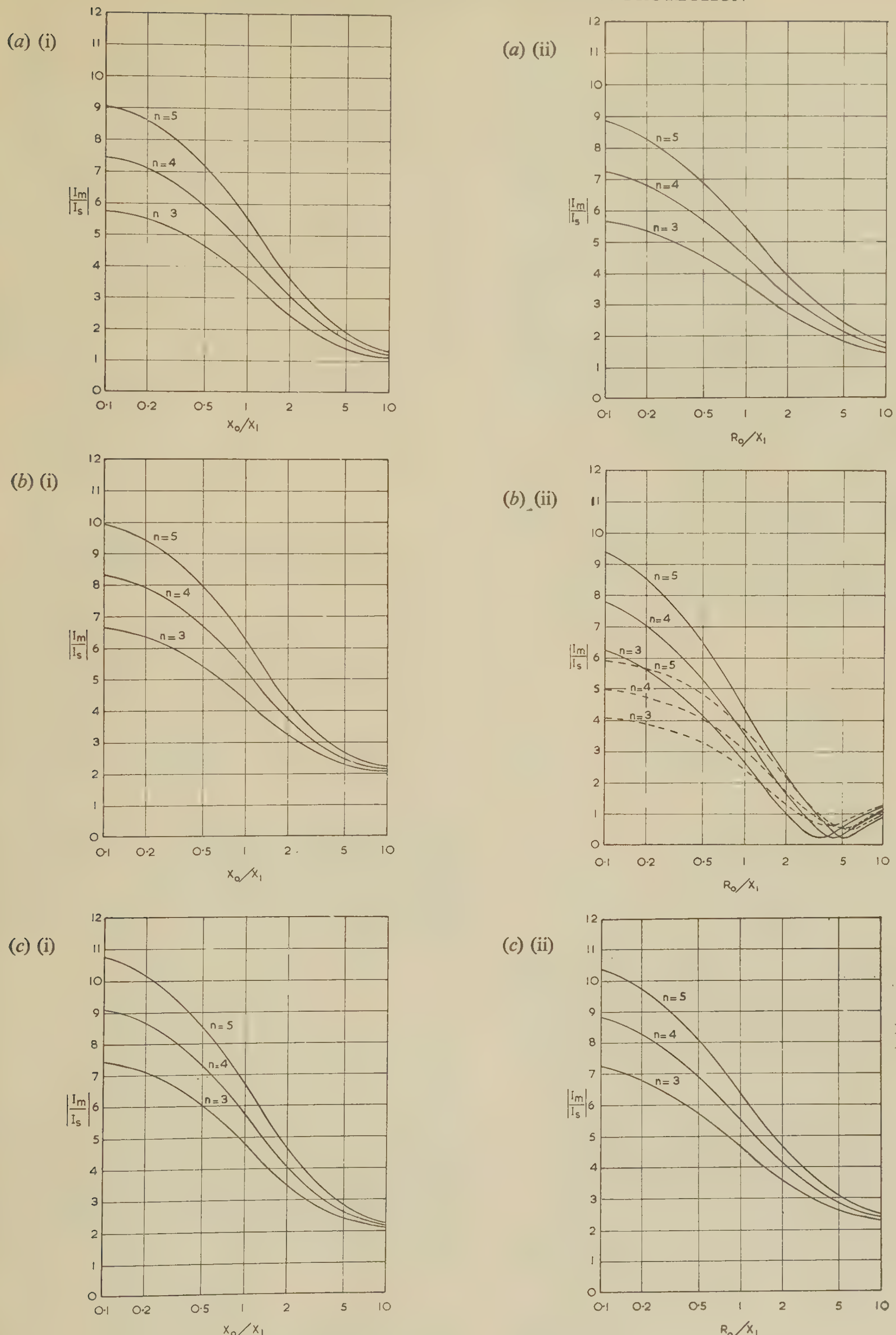


Fig. 9.—Relaying output from a summation transformer.

(a) Phase B–C–earth fault.
(i) $Z_0 = jX_0$.
(ii) $Z_0 = R_0$.

(b) Phase C–A–earth fault.
(i) $Z_0 = jX_0$.
(ii) ——— $Z_0 = R_0$
---- $Z_0 = R_0 + jX_1$.

(c) A–B–earth fault.
(i) $Z_0 = jX_0$.
(ii) $Z_0 = R_0$.

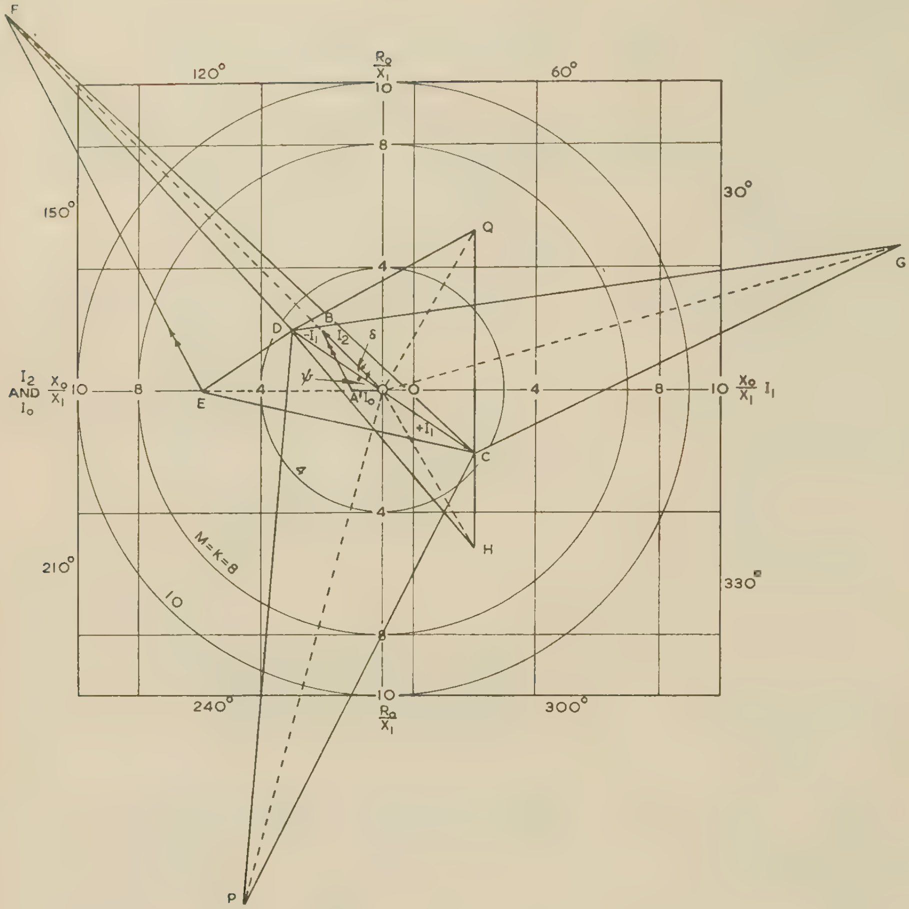


Fig. 10.—General chart for evaluating the value of the relaying quantity.

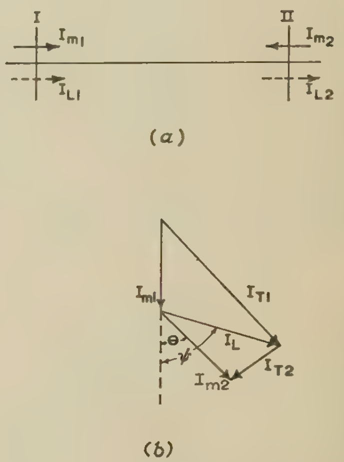


Fig. 11.—Combination of load and fault currents.

(a) Summation of currents at each end of the system.
(b) Vector relationships between load and fault currents.

This gives, for phase B–C–earth faults,

$$\mathrm{CF} \propto 6I_{2a} - I_{1a}$$
$$\mathrm{DF} \propto 6I_{2a} + I_{1a}$$
$$\mathrm{CE} \propto 6I_{0a} - I_{1a}$$
$$\mathrm{DE} \propto 6I_{0a} + I_{1a}$$

For phase A–B–earth faults the relative phases of I_1, I_2 and I_0 are obtained by maintaining I_1 unchanged and rotating I_2 and I_0 by $\boldsymbol{a}^2$ and $\boldsymbol{a}$ respectively; for phase C–A–earth faults, I_2 and I_0 are rotated by $\boldsymbol{a}$ and $\boldsymbol{a}^2$, respectively, I_1 being again unchanged. The different outputs for these faults are thus represented by:

I_m Phase A–B–earth faults	I_m Phase C–A–earth faults
$\mathrm{CG} \propto 6I_2 - I_1$	$\mathrm{CP} \propto 6I_2 - I_1$
$\mathrm{DG} \propto 6I_2 + I_1$	$\mathrm{DP} \propto 6I_2 + I_1$
$\mathrm{CH} \propto 6I_0 - I_1$	$\mathrm{CQ} \propto 6I_0 - I_1$
$\mathrm{DH} \propto 6I_0 + I_1$	$\mathrm{DQ} \propto 6I_0 + I_1$

To obtain the value of $|I_m/I_F|$, each of the above results obtained from the chart must be divided by the evaluated value of $|I_F|$ as given by eqn. (36).

(5) EFFECT OF LOAD CURRENT ON THE RELAYING QUANTITIES

Referring to Figs. 2 and 11(a), the relaying quantities I_{m1} and I_{m2} at ends I and II of the protected line are affected both in phase and amplitude by the load currents I_{L1} and I_{L2}, respectively. The effect of load current on the phase of the relaying quantity has already been discussed in a previous paper.[6] The effect on amplitude, however, depends on the magnitude of I_L as well as the phase angle δ between I_L and I_m, and is very relevant to the selection of relaying quantities discussed in the previous Sections.

Referring to Fig. 11(b), and assuming that

$$\theta = \text{Angle between } I_{m1} \text{ and } I_{m2}$$
$$\psi = \text{Angle between } I_{m1} \text{ and } I_L$$
$$|I_L| = |I_m \pm \Delta I_m|$$
$$\delta = (\pi - \psi) \text{ for } I_{m1}$$
$$= (\psi - \theta) \text{ for } I_{m2}$$

it can be shown that the magnitude of the resultant output $|I_T|$, is given by

$$|I_T| = \sqrt{\left(4|I_m|^2 \sin^2\frac{\delta}{2} \pm 4|I_m||\Delta I_m| \sin^2\frac{\delta}{2} + |\Delta I_m|^2\right)} \quad (37)$$

For $\Delta I_m = 0$, i.e. $|I_m| = |I_L|$, it follows that

$$|I_T| = 2|I_m| \sin\frac{\delta}{2} \quad . \quad . \quad . \quad . \quad . \quad (38)$$

Eqns. (37) and (38) are represented in Fig. 12 for $|I_L| = |I_m|$, $|I_L| > |I_m|$ and $|I_L| < |I_m|$. From this Figure it can be seen that, for $|I_L| = |I_m|$, the resultant output magnitude is sinusoidal, being zero for $\delta = 0$ and a maximum ($= 2|I_m|$) for $\delta = \pi$.

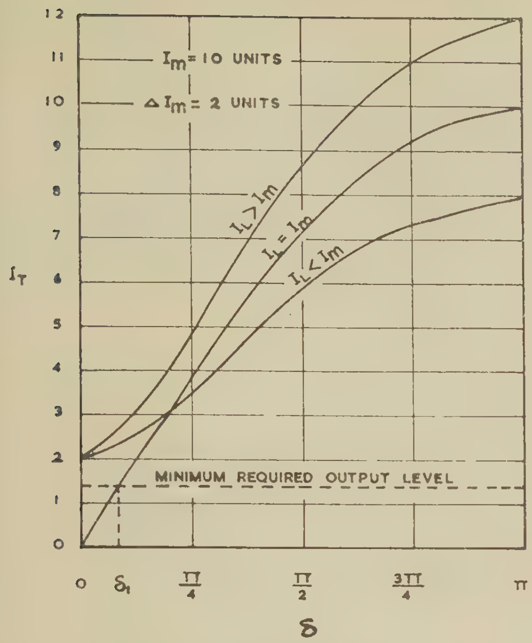


Fig. 12.—Effect of magnitude and phase of load current on the amplitude of the resultant relaying output.

For $|I_L| \gtrless |I_m|$, i.e. $|I_L| = |I_m \pm \Delta I_m|$, the magnitude of e output has a minimum value equal to $|\Delta I_m|$ for $\delta = 0$; e maximum value at $\delta = \pi$ is higher and lower, respectively, a value $|\Delta I_m|$ than the corresponding value for $|I_L| = |I_m|$. though the case of $|I_L| > |I_m|$ gives the highest output amplide at any angle δ, it is not desirable because of its adverse ects. The case of $|I_L| = |I_m|$, which was chosen as an cepted limit so far as phase effects are considered,[6] fails to ve adequate amplitude if $\delta < \delta_1$, as can be seen in Fig. 12; s condition is thus impermissible so far as amplitude is ncerned. This issue does not arise if it is known that $\delta > \delta_1$ a particular application. The case of $|I_L| = |I_m - \Delta I_m|$ ves a minimum amplitude $|\Delta I_m|$ for $\delta = 0$, and higher values any other values of δ; since this case was satisfactory as far phase effects were concerned it follows that, if $|\Delta I_m|$ is higher an the minimum required output level, it gives adequate performance for both phase and amplitude representation.

(6) CONCLUSIONS

Systematic analysis of the outputs of all possible phasequence segregating networks, together with that for the summan transformer, indicates that certain sequence networks are eatly to be preferred; the precise sequence network chosen in y particular case depends clearly on the system conditions, rticularly the values of zero phase-sequence resistance and actance. Reference to the curves of output from the various quence networks under differing fault conditions will indicate e best choice to suit the power-system parameters; in the inion of the authors a combination of positive and negative ase-sequence outputs provides the most versatile solution to e problem.

The very low or zero output from the summation transformer under some fault conditions makes it unlikely that its use will be widespread in the future and suggests that greater attention should be paid to the use of appropriate sequence networks. One advantage of phase-sequence networks over the summation transformer, of particular significance in some carrier schemes, is the way in which more than one independent output may be provided, e.g. for simultaneous starting and relaying purposes. The summation transformer is, however, a simpler device and is not frequency sensitive.

The complication introduced by the simultaneous presence of load and fault current in the power system may readily be anticipated in the case of sequence networks; this is so because load currents rarely contain significant proportions of negative and zero phase-sequence components, and thus add directly to the positive sequence component of the fault current. This enables simple expressions to be obtained which relate the minimum possible settings for earth faults to the proportions of the phase-sequence components which have been selected, as well as the ratio of maximum load to minimum fault currents. Furthermore, it is apparent from Section 5 that different practical consequences arise depending on whether the relaying outputs are compared in magnitude or in phase; both methods may, however, be used if the load current is less than the relaying quantity derived from the fault current by a suitable margin.

A general chart has been developed for easy and rapid evaluation of the derived relaying quantity as a function of any combination of phase-sequence components and different values of phase-sequence impedances. This enables graphical evaluations to be carried out for all fault conditions.

(7) ACKNOWLEDGMENT

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AN EXPERIMENTAL IMPEDANCE RELAY USING THE HALL EFFECT IN A SEMICONDUCTOR

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SUMMARY

The paper describes a new type of 'definite' impedance relay applicable to the protection of power transmission systems. Its operation is based upon a differential balance, under normal conditions, between the output from Hall effect in a semiconductor element and a rectifier unit. The experimental results obtained demonstrate the success of this instrument in principle and show that it has many advantages over the usual induction type of impedance relay.

(1) INTRODUCTION

The use of relays operated by a change of circuit impedance from normal working values for the protection of cables and transmission lines is a well-established practice.[1,2] Such relays are commonly of the induction type, having two elements operating to produce opposing torques on the same rotatable metal disc. One such instrument has an induction element of the kind frequently used in energy meters, and it is balanced against another similar element, giving a torque proportional to the square of the line voltage. Protective relays of this kind can be made to operate practically instantaneously for short-circuit faults occurring at any point along the associated transmission line, but, as would be expected, the arrangement is relatively insensitive to faults on extended parts of the network which do not reflect significant impedance changes to the point at which the relay is connected.

The advent of new semiconductors has led, in recent years, to many important applications of the Hall effect,[3–7] and the present proposal[8] offers interesting possibilities in the use of that effect for the construction of a 'definite' impedance relay capable of performing the same function as the conventional induction type of instrument and with greater simplicity. In the device to be described there are no moving parts, and since the load current itself is used directly to produce the magnetic field operating on the semiconductor, no current transformer is required. Moreover, with the air-gap housing the semiconductor in the magnetic circuit, there is virtually no danger of saturation, even under the most severe fault conditions. The physical size of this Hall-effect relay is much smaller than that of the equivalent induction type, whilst its sensitivity is quite adequate to make it of practical application to large power transmission systems.

(2) PRINCIPLE OF OPERATION

Before discussing the operation of the Hall-effect relay, it will be helpful to refer to the more conventional type.

Fig. 1(*a*) shows a typical directional impedance relay incorporating induction-voltmeter and induction-wattmeter elements operating in opposition on the same eddy-current disc.

Written contributions on papers published without being read at meetings are invited for consideration with a view to publication.

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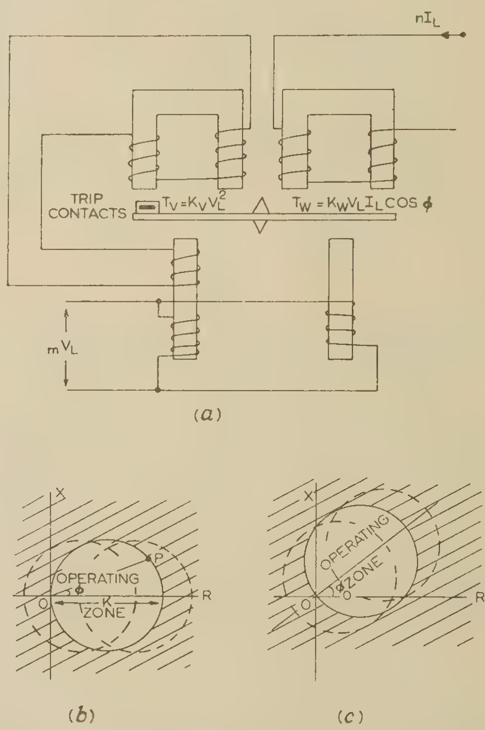

Fig. 1.—Operating characteristics of induction-type directional-impedance relay.

(*a*) Circuit diagram.
(*b*) Zero phase shift.
(*c*) With phase shift.

The torque on the disc due to the voltmeter element is

$$T_V = K_V V_L^2 \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

and the corresponding torque due to the wattmeter element is

$$T_W = K_W V_L I_L \cos\phi \quad . \quad . \quad . \quad . \quad . \quad (2)$$

so that when these torques are balanced

$$K_V V_L^2 = K_W V_L I_L \cos\phi \quad . \quad . \quad . \quad . \quad (3)$$

from which the line impedance is

$$Z = \frac{V_L}{I_L} = \frac{K_W}{K_V}\cos\phi = K\cos\phi \quad . \quad . \quad . \quad (4)$$

When the impedance of the transmission-line circuit fall sufficiently below its normal operating value and the torque o the wattmeter element thereby becomes the larger one, the dis rotates to close the trip contacts.

Plotting resistive and reactive components R and X, respec tively, of the line impedance Z as in Fig. 1(*b*), we ge $Z = \sqrt{(R^2 + X^2)}$, and for the condition represented by eqn. (4

e locus of Z must be a circle of diameter K, so that the zone operation of the relay for different line power factors would be pected to be within that circle. If, however, a phase shift ϕ_0 deliberately introduced into the relay network, the diameter the circle which circumscribes the operating zone is swung und, as shown in Fig. 1(*c*), and furthermore when positive or gative bias is applied, this circle (shown dotted) is shifted to e side or the other of the origin.

In the relay used for the present experiments, the wattmeter ment is represented by a Hall-effect unit and the voltage-uared element by a rectifier. Referring to Fig. 2, it will be

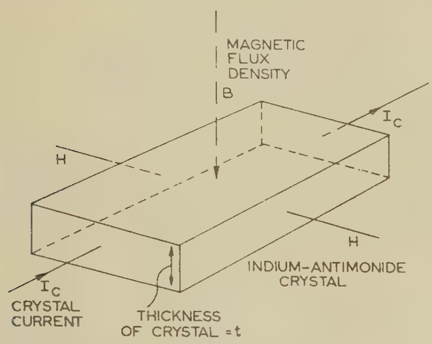

Fig. 2.—Mechanism of Hall effect.

en that a conducting plate immersed in an externally applied agnetic field B, and supporting a current I_C by reason of mobile rriers within it predominantly of one sign, will produce an n.f. V_H between the terminals HH given by

$$V_H = \frac{\mathscr{R}_H B I_C}{t} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

here $\mathscr{R}_H$ is the Hall coefficient for the material.

This so-called Hall effect arises from the interaction of the agnetic field B with that due to the current I_C associated with e mobile carriers in the semiconductor and is proportional, at y instant, to the product of these quantities. Thus, when B produced by the line current and I_C determined by the line ltage, the time-average of the Hall e.m.f., $\bar{V}_H$, gives a measure the true power ($V_L I_L \cos\phi$) in the circuit. In general the all output voltage from the crystal contains both a d.c. and a uble-frequency a.c. (100 c/s) component, but only the former utilized here. Fig. 3 shows a Hall-effect unit of this kind rming the wattmeter element of the protective relay. The all e.m.f., $\bar{V}_H$, appears across the resistor R_4 (whose value is rge compared with the internal resistance of the crystal), and is e.m.f. is normally balanced against the corresponding time-erage, $\bar{V}_B$, of the output from the square-law rectifier across R_3. these circumstances, the voltmeter V shows no deflection, and nce we have established exactly the same conditions as in the duction type of relay, eqn. (4) applies.

In the event of a fault occurring, the line current rises and the pedance at the point at which the relay is connected falls. us $\bar{V}_H$ becomes larger than $\bar{V}_B$ and an out-of-balance voltage, appears which can be used to operate an ordinary electro-agnetic relay. The inertia of the relay makes it incapable of sponding to the a.c. component of V, and any alternating rrent in this part of the circuit is largely suppressed by the ductance of the relay winding.

In practice, it is convenient to use a polarized relay having o windings connected in opposition and excited respectively $\bar{V}_B$ and $\bar{V}_H$. When the unbalanced m.m.f.'s are sufficient, e relay operates and closes the trip circuit of a circuit-breaker.

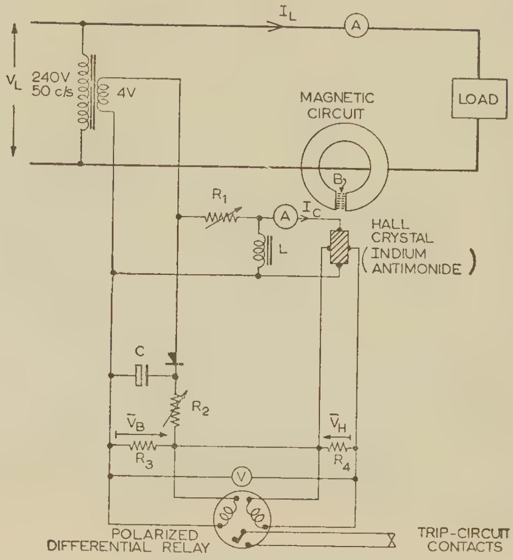

Fig. 3.—Test circuit arrangement.

I_L = 100–300 amp. R_1 = 12 ohms.
I_C = 350 mA. R_2 = 5 kilohms.
L = 35 mH. R_3^* = 10 ohms.
C = 100 μF. R_4^* = 1 kilohm.

* Not required when polarized differential relay is used.

(3) DETAILS OF EXPERIMENTAL APPARATUS AND RESULTS OBTAINED

A crystal of indium antimonide, having dimensions 0·2 in × 0·1 in × 0·013 in, was mounted between thin sheets of mica in the air-gap of a magnetic circuit formed from a packet of ring-shaped Stalloy-iron laminations, 1 in outside diameter and 0·5 in inside diameter. The conductor carrying the line current was passed through the centre of the iron ring, as in a bar-type current transformer.

To avoid over-heating, the maximum allowable dissipation in the crystal was about 1 mW per square millimetre of surface area and this corresponded to the working current of 350 mA through the crystal. Arrangements were made to supply the crystal current from the secondary of a step-down voltage transformer, as indicated in Fig. 3, and the inductor, L, was introduced to compensate for the phase-angle error for which the transformer was responsible.

Fig. 4 shows the experimental results obtained for a constant

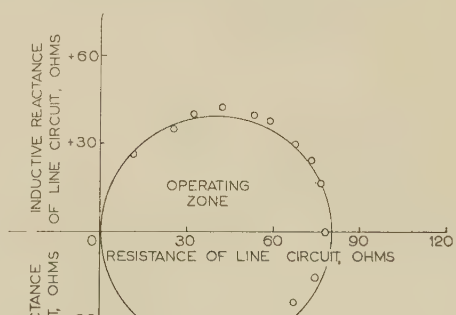

Fig. 4.—Graph of line circuit impedance to give constant out-of-balance voltage.

O Experimental points.

out-of-balance voltage applied to the differential relay and at various line power factors, whilst the circle represents the corresponding theoretical operating zone.

If a polarized relay is used, the direction of movement of the tongue depends upon the direction of the power. When the impedance of the line circuit fell within the operating zone, the unbalance of m.m.f. applied to the differential relay was sufficient to operate it. In these circumstances, an increase in the line current of 100 amp was found to trip a relay having windings of resistance 100 ohms and a minimum actuating current of 250 μA. Although the current-carrying capacity of the contacts of this relay was only about 10 mA, the output could be used to actuate another larger relay having contacts capable of passing sufficient current to trip the circuit-breaker.

In practice, the impedance presented by a short-circuit fault may be highly reactive, and to allow for this the operating zone of the impedance relay described can be conveniently phase shifted into the most appropriate quadrant by the introduction of a phase-shifting network in the crystal-current circuit of the Hall-effect unit.

(4) CONCLUSIONS

As the experimental results show, this Hall-effect protective relay behaves, as anticipated, in a manner very similar to the more conventional induction-operated device, and consequently can be designed to take its place in a power system. The new type of impedance relay has ample sensitivity for most applications and possesses the advantages of small physical size, simplicity, linear operation over a wide range of currents and relatively low cost.

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HE MEASUREMENT OF TRANSIENT TORQUE AND LOAD ANGLE IN MODEL SYNCHRONOUS MACHINES

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SUMMARY

he paper deals with the development of equipment for measuring torque and load angle of an electrical machine under transient ditions and its use in verifying some theoretical results. The ipment is used in conjunction with a 'micro-alternator', which is a all machine specially designed to simulate a large generator.

he torque meter uses resistance strain gauges mounted on a special pling connected mechanically to the machine shaft. The load- le meter operates by generating a succession of pulses which modu- the intensity of an oscillograph beam as it traverses a periodic ve.

he experiments recorded relate to the following conditions:

(*a*) Oscillations superimposed on steady operation as a synchro- ous machine.

(*b*) Sudden short-circuit of an alternator.

LIST OF SYMBOLS

a = Electrical damping factor.
c = Mechanical damping factor.
C = Effective damping coefficient of the machine.
H = Inertia constant.
J = Moment of inertia.
K = Effective elastic coefficient of the machine.
m = Angular frequency of the oscillation.
M = Magnification factor.
n = Modified mechanical damping factor.
r_1, r_2 = Resistances of the induction motor (Section 4).
r_2 = Negative sequence resistance of the synchronous machine (Section 5).
r_a = Armature resistance of the synchronous machine.
T_e = Electrical torque.
T_s = Shaft torque.
V = Supply voltage.
V_0 = Open-circuit voltage for a given field current.
X_1, X_2 = Leakage reactances of the induction motor (Section 4).
X_2 = Negative sequence reactance of the synchronous machine (Section 5).
X_d, X_q = Synchronous reactances.
X'_d = Transient reactance.
X''_d, X''_q = Sub-transient reactances.
$_q(jm), X_q(jm)$ = Operational impedances at frequency m.
X_m = Magnetizing reactance of the induction motor.
δ = Load angle.
δ_0 = Steady load angle.
λ = Switching angle.
τ_a = Armature time-constant.
τ'_d = Transient time-constant.
τ''_d, τ''_q = Sub-transient time-constants.
ϕ, ϕ_n = Angles of lead in the mechanical system.
ω = Angular frequency of the supply.
ω_e = Angular frequency of a component of electrical torque.
ω_c, ω_n = Actual, modified natural angular frequency of the mechanical system.
Δ before a symbol indicates a small change.

(1) INTRODUCTION

During any transient condition of operation of a synchronous machine the torque developed is one of the important quantities, and theoretical methods for determining it under different conditions have been available ever since Park published his classic paper in 1929.[1] There has, however, been very little direct experimental verification of the theories, mainly because of the difficulty of measuring the torque developed in a large machine. The paper gives the results of some measurements carried out on small laboratory machines. On a small model the task of measuring the torque is less formidable than on a large machine, but it is essential that the laboratory apparatus used for the experiments shall be such that the results obtained can be applied to the large generators used in power systems.

For the later tests the machine used was a 'micro-alternator',[2] which is a small machine, rated at 2·25 kVA, specially designed to simulate the electromagnetic and mechanical characteristics of a large synchronous machine. The first part of the investigation, which was made before the micro-alternator was available, used a small slip-ring induction motor operated as a synchronous machine.

For measuring the transient torque, a special coupling was constructed for mounting between the alternator and a d.c. motor; it uses four resistance strain gauges mounted on a thin tube which forms part of the coupling. The apparatus measures the shaft torque external to the machine and not the electrical torque developed at the air gap, but one may be deduced from the other if the characteristics of the mechanical system are known.

The 'instantaneous load angle', defined in Section 3, is another important quantity in a synchronous machine under transient conditions and a special load-angle meter was developed to record its variation with time. The equipment makes use of pulses generated at definite rotor positions to modulate the beam of a cathode-ray oscillograph at a definite point in each cycle.

After any sudden change in the conditions of operation of a synchronous machine, caused by a fault or other switching operation in the external system, transient currents flow in all the windings and a transient torque is developed. The torque can be divided into an alternating part having components at supply and higher harmonic frequencies, and a slowly-varying part which is either unidirectional or a slow oscillation.

The alternating torque may, after a severe fault, reach a dangerous value during the first few cycles, but it dies away rapidly afterwards. The slowly-varying torque component is,

Vritten contributions on papers published without being read at meetings are ted for consideration with a view to publication.
Dr. Adkins is, and Dr. Sudan and Mr. Manohar were formerly, in the Department Electrical Engineering, Imperial College of Science and Technology, University of ndon. Dr. Sudan is now at Cornell University, New York, and Mr. Manohar is h the Tata Power Co., Bombay.

in effect, the mean value over a cycle of the resultant oscillating torque. It is important because it causes the rotor angle to swing, and is thus a decisive factor in determining the transient stability of the system.

The construction and application of the measuring equipment were carried out in several stages. The paper describes the apparatus and gives the results of measurements made under the following conditions:

Small oscillations in a synchronous machine connected to a fixed supply.—The pulsations of both torque and load angle were measured. The frequency was less than 3 c/s and the torque was small (about 10% of full load).

Sudden short-circuit of an unloaded alternator.—The main interest here was in the rapidly alternating torque which contained components of frequencies up to 100 c/s and had a high peak value (up to six times full load).

The equipment was used later for a more comprehensive investigation into other transient conditions, during which the slowly varying torque caused the load angle to swing after the occurrence of a fault. The results of this work are given in a companion paper.[3]

(2) THE TORQUE METER

(2.1) General Arrangement

The measurement of the torque of a rotating machine presents considerable difficulty, particularly when it is required to record the instantaneous values under rapidly varying conditions. Many methods have been proposed, including the following:

(*a*) Measurement of acceleration.[4,5,6]
(*b*) Measurement of the angular deflection of the shaft.[7]
(*c*) Measurement of the strain in the rotor shaft.[8]
(*d*) Measurement of the strain in the stator support.[9]
(*e*) Direct measurement of the torque by piezo-electric crystals.[10]

The method selected for the present investigation is based on the measurement of the strain in a specially constructed torque coupling mounted between the test machine and a load machine. Method (*c*) is more direct and convenient than (*a*), (*b*) or (*d*) and introduces fewer practical difficulties than (*e*). With (*c*), the coupling can have greater stiffness than is practicable for the other methods.

The strain is measured by means of four resistance strain gauges in bridge connection. The gauges are cemented on the outer surface of a tube, as shown in Fig. 1. The axes of the gauges are directed along the lines of principal tensile and compressive strain, which are at 45° to the axis of the tube when it is subjected to torsion. The changes of resistance of the strain gauges, indicated in Fig. 2, produce a signal output proportional

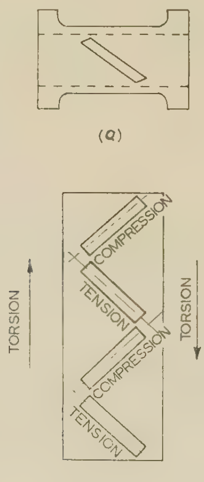


Fig. 1.—Torque tube with strain gauges.
(*a*) Plan view.
(*b*) Developed view.

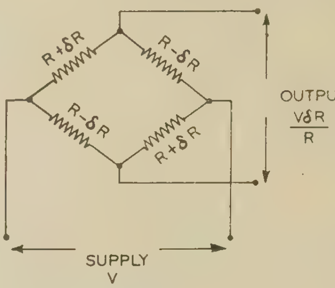


Fig. 2.—Bridge connection of strain gauges.

to the torque in the tube. The main difficulties arise because the voltage signal is very small (of the order of a millivolt) and because connections to the measuring apparatus have to be made through slip-rings. In order to obtain as large a signal as possible the gauges have a high resistance and the tube has a modulus of cross-section which is much smaller than that of the machine shaft. Even so, the disturbance due to the slip-rings is too large compared with the signal. The torque coupling is therefore constructed so that an amplifier, connected between the gauges and the slip-rings, can be mounted inside it, thus reducing the relative magnitude of the disturbance.

Fig. 3 is a sectional drawing of the torque coupling. By the

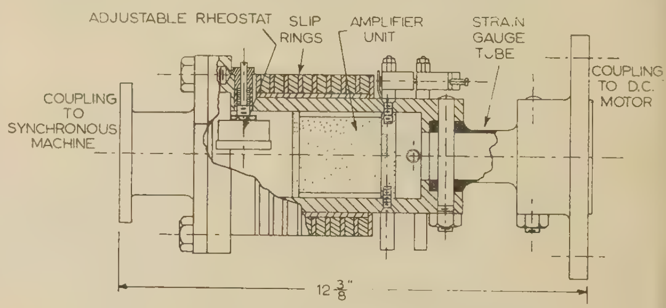


Fig. 3.—Sectional drawing of the torque coupling.

use of appropriate half-couplings the device can be mounted between any two machines of suitable size. The tube carrying the strain gauges can be changed so as to vary the cross-section or material of the tube or the resistance of the gauges. The slip-rings are made of stainless steel and the brushes, of which there are two on each slip-ring placed diametrically opposite to each other, are of silver graphite with 85% silver to reduce the disturbance due to the brush contact. The slip-ring assembly is carefully impregnated with insulating varnish and the gauges are sealed off with a protective wax to give high leakage resistance. A mild-steel tube of $1\frac{3}{8}$ in outside diameter, $\frac{1}{16}$ in thickness and $\frac{7}{8}$ in effective length was used for all the tests. With a torque of 14·1 lb-ft, corresponding to 3 kW at 1 500 r.p.m., the stress at the outside of the tube along the lines of principal stress (at 45° to the axis) is 1 140 lb/in^2 and the corresponding strain is 40×10^{-6}.

The stress in the tube, although much greater than that in a normal machine shaft, is still low, but it is not feasible to increase it by using a thinner tube because, apart from the need to carry heavy peaks, the increased flexibility would reduce the mechanical natural frequency. Moreover there are inevitable bending

esses in the tube owing to the weight of the shaft and to errors alignment between the machines. The bending moment, ich pulsates once per revolution, causes an oscillating voltage be superimposed on the main voltage obtained from the ain-gauge bridge. With identical gauges and perfect align-nt at 45°, a bending or shear stress in the tube would produce voltage. Even after careful attention has been paid to the gnment of the machines and gauges, however, the disturbance ised by this effect is equivalent to a torque pulsation of the der of 30% of full load.

The development of the torque meter was carried out in two ges. In the first experimental equipment the gauges were oplied with an alternating voltage in order that a.c. amplifiers uld be used. The final version used direct current and d.c. plifiers.

(2.2) Torque Meter Equipment (A.C. Version)[11]

For the small oscillating torque measured during the first stage the investigation, the strain was of the order 5×10^{-6}. High-istance Nichrome gauges (10 000 ohms) were therefore used, that when the bridge was supplied at 50 volts, the output nal was about 0·5 mV. The gauges were supplied with ernating current at 1 000 c/s and a.c. amplifiers were used to tain the high amplification required.

Fig. 4 is a block diagram of the circuit. The bridge is supplied

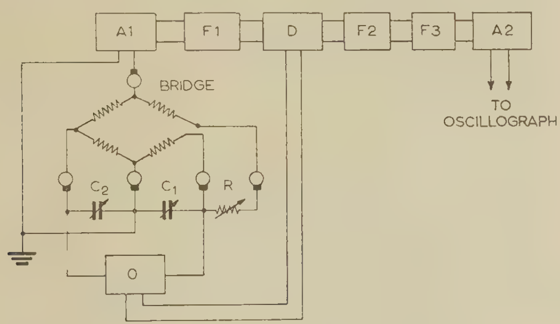


Fig. 4.—Block diagram of the torque-meter connections.

1 000 c/s from the oscillator O, and the bridge output, which a 1 000 c/s carrier wave modulated by the waveform of the lsating torque, is amplified in A1. The five slip-ring connec-ns are indicated on the diagram. A filter, F1, is introduced this stage to eliminate any harmonics in the carrier wave, and filtered output is demodulated by the phase-sensitive detector

The filter F2 eliminates the carrier wave from the demodu-ed signal, which is then proportional to the shaft torque. wever, with the machine running at 1 500 r.p.m., the slip-ring ntacts and the bending moment introduce an appreciable c/s disturbance which is eliminated by the filter F3. The tput is fed to the d.c. pre-amplifier A2 of the oscillograph.

The bridge must be balanced both with resistance and capaci-ice to compensate for differences between the resistances of four gauges and between their capacitances to earth. A od capacitative balance, moreover, reduces the error due to variation of the frequency of the oscillator output. The chrome gauges have a relatively high temperature coefficient l it is necessary to switch them on in advance in order to ain a stable temperature before taking readings.

The torque meter gave satisfactory results for the oscillation ts, but the use of alternating current in the bridge introduced isiderable complication. The equipment was not suitable for asuring short-circuit torques because of the filter F3, which minated oscillating components above 25 c/s.

(2.3) Torque Meter Equipment (D.C. Version)[12, 13]

In the modified equipment the strain-gauge bridge was supplied with direct current, and a special transistor amplifier was developed for mounting on the coupling. This amplified the strain-gauge signal in order to reduce the effect of the disturbance caused by the slip-rings. A preliminary attempt to use a built-in valve amplifier was unsuccessful because its supplies had to be fed in through slip-rings. The transistor amplifier has the advantage that it is completely self-contained since it requires no heater supplies and its small batteries can readily be mounted on the rotating coupling.

The gauges were of lower resistance than before (1 000 ohms) and were of cupro-nickel. The lower resistance suits the transistors and the lower temperature coefficient of cupro-nickel is an advantage. The location inside the steel tube of the coupling helps to keep the temperature constant and to reduce variations of the transistor characteristics. Each stage has series feedback and all resistances are wire-wound.

Fig. 5 is a circuit diagram of the transistor amplifier in which

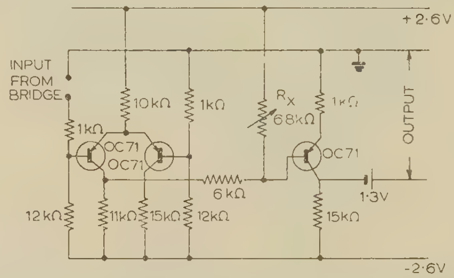


Fig. 5.—Circuit diagram of the transistor amplifier.

a differential amplifier circuit, corresponding to the long-tailed pair of valve amplifier practice, is used for the first stage. The principal cause of drift in transistors is the variation of the collector leakage current with temperature. The two differential transistors were selected as the best matched pair in an available total of six, after performing tests for drift on several combinations. The first stage is followed by an ordinary common-emitter stage. With this arrangement the drift occurring during the time required to take an oscillogram was negligible. The drift over longer periods could be corrected by the resistance R_x.

The bending-moment disturbance causes difficulty in measuring small rapidly oscillating torques. However, such measurements are rarely required, since the main interest when the torque is small is in the slowly varying components. A filter is then necessary to eliminate the pulsating torques.

(3) THE LOAD-ANGLE METER

(3.1) General

The load angle of a synchronous machine connected to a fixed 3-phase supply is defined as the electrical angle between the actual position of the rotor at any instant and a uniformly rotating reference line related to the supply voltage. Because of the inertia of the rotor the load angle can only change slowly. The oscillograph record of the transient load angle was obtained, by the methods described below, as a series of dots spaced at intervals of one cycle of the alternating voltage. The load-angle measurement depends on the production once per cycle of a sharp pulse which modulates the intensity of the beam of a cathode-ray oscillograph. The beam traverses a periodic wave across the screen in such a way that the points which are illuminated when the pulse is applied indicate the load angle as a function of time (see Figs. 6, 7 and 12).

The pulse may be produced by a magnetic pick-up or by an electronic pulse generator supplied from an a.c. tachometer generator coupled to the main machine. Again, the periodic wave traversed by the beam may be a sine wave taken directly from the machine terminals or a sawtooth wave generated by the time-base of the oscillograph. Either method of pulse generation may be used with either type of periodic wave.

The first equipment developed, which used the pulse from a magnetic pick-up in conjunction with a sinusoidal wave, was applied to the measurement of small oscillations. For the later tests, recorded in Reference 3, an electronically generated pulse was used with a sawtooth wave.

(3.2) Load Angle Meter (First Version)[14]

The equipment used for the measurement of small oscillations is illustrated in Fig. 6. The pulse is obtained from a magnetic

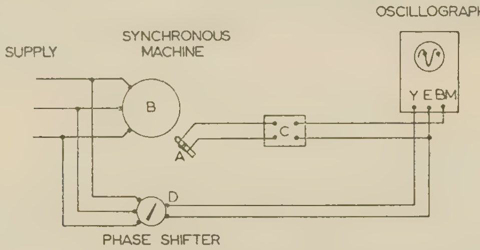


Fig. 6.—Circuit diagram of the load-angle meter (first version).

pick-up, A, mounted near to a rotating disc, B, provided with two steel projections at diametrically opposite points. (The test machine has four poles.) The output from the pick-up is applied to a differentiating circuit, C, in order to obtain a sharp pulse for applying to the terminal BM of the oscillograph.

The terminal voltage of the machine, which provides the synchronous reference, is connected to the Y-plate of the oscillograph through a phase shifter, D. If the oscillograph beam were continuously energized a sine wave would appear on the screen, but, as a result of the modulation of the beam intensity by the pulses obtained from the pick-up, only the spots appear at the instants when the steel projections pass the pick-up armature. Thus, the displacement of the spot is a measure of the load angle. For a given location of the pick-up in relation to the machine windings and the steel projections there is one setting of the phase shifter (the neutral position) for which zero displacement corresponds to zero load angle. The displacement is then proportional to sin δ.

If the phase shifter is moved through an angle δ_0 from the neutral position, the displacement of the oscillograph beam is proportional to $\sin(\delta - \delta_0)$. For the measurement of small oscillations relative to a steady operating condition of the synchronous machine, the phase shifter is set so that the oscillograph deflection is zero for the angle δ_0 corresponding to the steady load. During an oscillation of which the amplitude is less than 10°, the oscillograph deflection is very closely proportional to $\Delta\delta = \delta - \delta_0$.

(3.3) Load Angle Meter (Second Version)[15]

In the second equipment, a succession of pulses, which modulates the beam intensity of the oscillograph, is obtained from a small a.c. tachogenerator coupled to the synchronous machine. A sharp pulse is generated once per cycle at the instant of zero voltage by an electronic pulse generator.

A second pulse generator produces pulses from the a.c. supply at the instants when the voltage passes through zero. The pulses are used to trigger the normal oscillograph time-base and thus to cause the beam to traverse the X-axis. The Y-plates are not energized. To record the load-angle variations, a camera is mounted so that the film moves at a constant speed in the direction of the Y-axis.. Fig. 7 illustrates the manner in

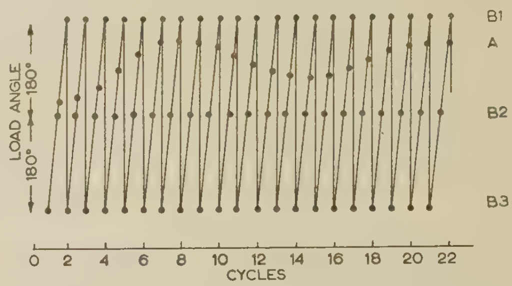


Fig. 7.—Diagram illustrating the method of recording the load angle (second version).

which the load angle is recorded. If the beam were continuously illuminated, the trace on the film would follow the sawtooth path shown by the thin line. However, only the spots illuminated by the pulses can be seen. The line A traced by the spots illuminated by the pulses from the tachogenerator gives the instantaneous load angle.

In order to indicate the zero and scale of the load-angle curve, the beam is also modulated by the pulses obtained from the machine terminal voltage, so as to show the spots on the straight lines B_1, B_2, B_3.

Compared with the first version of the torque meter, the second version requires more elaborate equipment, including the tachogenerator coupled to the main alternator, but it gives more accurate results. The use of the sawtooth wave makes it possible to record the load angle over any range, for example when the alternator slips through multiples of 360°. It is essential to use a high-grade oscillograph having a high sensitivity of modulation intensity and a well synchronized time-base.

(4) SMALL OSCILLATIONS RELATIVE TO A STEADY LOAD CONDITION

(4.1) Theory of Small Oscillations in a Synchronous Machine

In a simple mechanical system a damping force is defined as one dependent on, and, in the ideal case, proportional to the speed of the moving body. A synchronous machine is, under certain conditions, analogous to a rotating mechanical system having inertia, stiffness and viscous damping. The displacement angle is, however, not the actual angular position at any instant but is the load angle, δ, by which the rotor position departs from a reference position rotating at synchronous speed. The equation of motion is

$$J\frac{d^2\delta}{dt^2} + C\frac{d\delta}{dt} + K\delta = T_s \quad . \quad . \quad . \quad . \quad (1)$$

The moment of inertia, J, is related to the inertia constant, H, of the synchronous machine and the angular frequency, ω, of the supply by $J = 2H/\omega$.

If the system is subjected to a sinusoidal torque oscillation at angular frequency m represented by a vector $\boldsymbol{\Delta T_s}$, the vector $\boldsymbol{\Delta\delta}$ for the angular pulsation is given by

$$-m^2J\boldsymbol{\Delta\delta} + jmC\boldsymbol{\Delta\delta} + K\boldsymbol{\Delta\delta} = \boldsymbol{\Delta T_s} \quad . \quad . \quad . \quad (2)$$

In the synchronous machine the elastic and damping torques

e produced by electrical action; that is, they are together ual to the electrical torque ΔT_e. Thus

$$\Delta T_e = (K + jmC)\Delta\delta \quad . \quad . \quad . \quad . \quad . \quad (3)$$

$$\Delta T_s = \Delta T_e - m^2 J\Delta\delta \quad . \quad . \quad . \quad . \quad . \quad (4)$$

The theory of small oscillations in a synchronous machine nnected to a fixed 3-phase supply has been studied in connec-on with the forced oscillations in Diesel-driven alternators. A ller treatment is given in Reference 16, Chap. IX, from which n. (5) is taken. If the amplitude of the oscillation is small, a usoidal pulsating torque causes all the quantities in the achine to oscillate sinusoidally at the same frequency. The tio of the vectors representing the electrical torque and the ad-angle pulsations is given as a complex number by the llowing expression:

$$\frac{\Delta T_e}{\Delta\delta} = \frac{VV_0}{X_d}\cos\delta_0 + V^2\left[\frac{1}{X_q(jm)} - \frac{1}{X_d}\right]\cos^2\delta_0 + V^2\left[\frac{1}{X_d(jm)} - \frac{1}{X_q}\right]\sin^2\delta_0 \quad (5)$$

It is evident from eqn. (3) that K and mC are given by the al and imaginary parts of the expression in eqn. (5).

In the ideal mechanical system, K and C are constants for y condition of operation. The equations governing the haviour of a synchronous machine are, however, much more mplicated than eqn. (1), and the analogy between it and the echanical system only applies under certain restricted condi-ons. The values of K and C deduced from eqn. (5) only ply for small oscillations, and it can be seen from the equation at K and C are functions not only of m but also of δ_0, V_0 and V.

(4.2) The Test Machine and its Constants

In order to check the values of K and C by direct measurement, $7\frac{1}{2}$ h.p. 4-pole 110-volt 50 c/s 3-phase star-connected slip-ring duction motor was used as a synchronous machine by exciting e rotor with direct current. The rotor winding was connected shown in Fig. 8, with the direct current passing through one

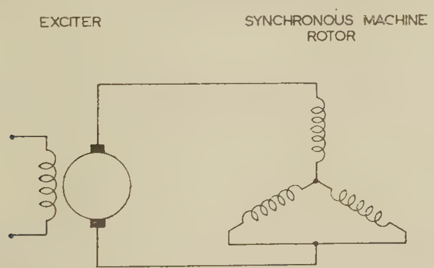


Fig. 8.—Rotor connections of the induction motor used as a synchronous machine.

hase in series with the other two connected in parallel, to provide damper circuit on the quadrature axis. There is no damper rcuit on the direct axis. For operation as a synchronous achine an appropriate rating is 3 kVA.

Per-unit quantities are used throughout. The per-unit values e based on unit voltage of 63·5 volts (phase) and unit current 15·7 amp.

The per-unit resistances and reactances and the inertia constant ere determined by the tests indicated; X_1 and X_2 are assumed be equal:

$r_1 = 0{\cdot}011$ (d.c. measurement).
$r_2 = 0{\cdot}026$ (impedance test).
$X_1 = X_2 = 0{\cdot}04$ (impedance test).
$H = 2{\cdot}0$ sec (deceleration test).

When the induction motor is operated as a synchronous machine with the rotor connected as in Fig. 8, the direct- and quadrature-axis operational impedances, $X_d(jm)$ and $X_q(jm)$, are given by the equivalent circuit of Fig. 9. Their values are equal,

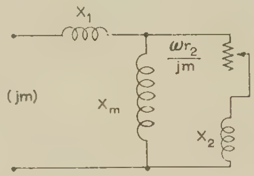


Fig. 9.—Equivalent circuit for the operational impedance, $X_d(jm)$.

apart from the effect on $X_d(jm)$ of the small additional impedance of the d.c. source in the field circuit. The semicircular vector locus of $X_d(jm)$, calculated for the test machine with no external field impedance, is shown as a full line in Fig. 10.

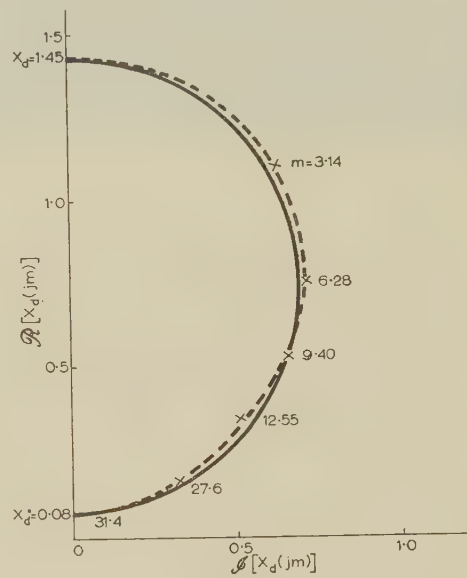


Fig. 10.—Vector locus of the operational impedance, $X_d(jm)$.
---- Test curve.
—— Calculated curve.

An experimental check of the operational impedance was obtained by making standstill impedance tests at different frequencies, using the method explained in Reference 17. The experimental vector locus is shown by a dotted line in Fig. 10.

(4.3) Measurement of the Elastic and Damping Coefficients

The arrangement of the equipment used for the oscillation tests is shown in Fig. 11. The test machine runs as a synchronous motor and is rigidly coupled, through the torque coupling,

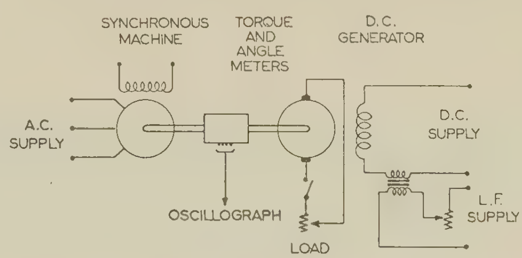


Fig. 11.—Test arrangement for measuring small oscillations.

to a d.c. generator which is loaded with a resistance. The d.c. machine is separately excited from a d.c. source in series with a low-frequency a.c. source provided by a transformer supplied from an a.c. commutator machine. Because of the low-frequency excitation, both the load angle and the torque in the coupling pulsate sinusoidally. The steady load was first set with the low-frequency supply disconnected, and the angle δ_0 was measured by adjusting the phase shifter (see Fig. 6) to give zero deflection.

A typical oscillogram recording the pulsations of torque and load angle is shown in Fig. 12. A split-beam oscillograph was

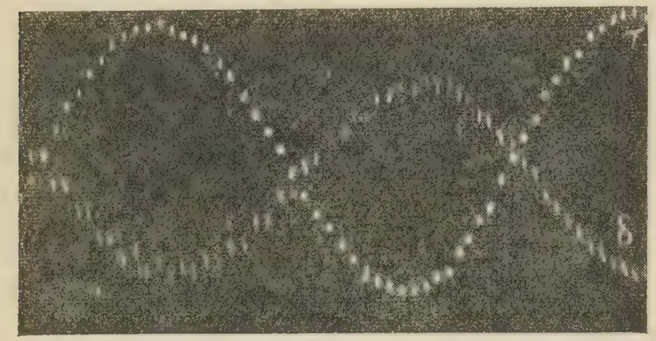


Fig. 12.—Typical oscillograms of torque and load-angle oscillations.

used, with the result that both traces appear as series of dots because both beams were modulated by the pulses. Alternate dots on the angle curve are slightly out of line because the two steel projections are not exactly 180° apart: one set of alternate dots is, in fact, sufficient to determine the curve. The magnitudes of ΔT_s and $\Delta\delta$ and the phase angle between them were measured on the oscillogram and used to determine the complex number $\Delta T_s/\Delta\delta$. The quantities K and mC were obtained as the real and imaginary parts of the complex number $\Delta T_e/\Delta\delta$ calculated from eqn. (4).

Fig. 13 shows the values of K and mC calculated from eqn. (5) for different values of δ_0 at three different oscillation frequencies. The points obtained by measurement are also shown. During these tests, the machine was supplied at normal voltage, and the steady load was kept constant as the load angle was varied by adjusting the excitation.

The agreement between the measured and calculated values is reasonable, although the accuracy of the measurements made from the oscillograms is not high. In particular, the phase angle between the pulsations of torque and load angle may be two or three degrees in error.

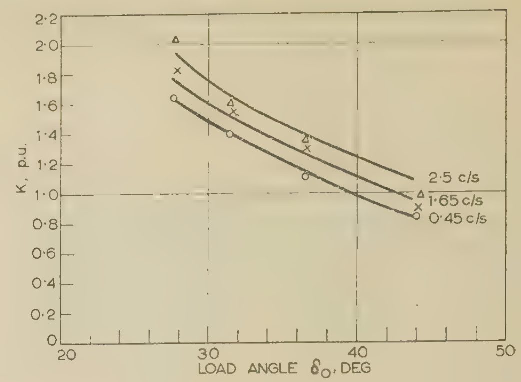
(4.4) Approximate Formula for the Damping Coefficient C

It has been proposed that a damping coefficient which depends only on the angle δ_0 can be used for calculating swing curves during fault conditions. The following expression, derived with certain approximations from Park's equations, is given by Crary:[18]

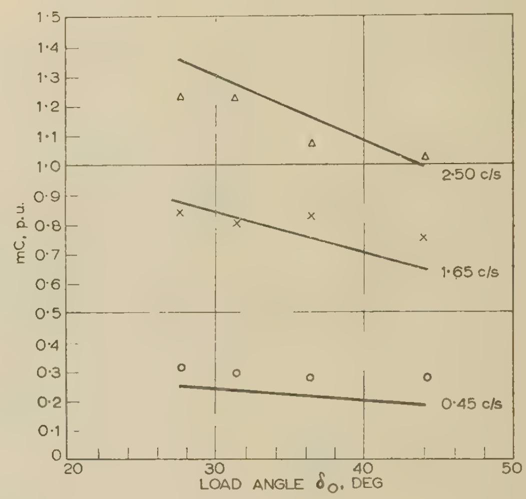
$$C = V^2\left[\left(\frac{1}{X''_d} - \frac{1}{X'_d}\right)\tau''_d \sin^2\delta_0 + \left(\frac{1}{X''_q} - \frac{1}{X_q}\right)\tau''_q \cos^2\delta_0\right] \quad (6)$$

If the two coefficients of $\sin^2\delta_0$ and $\cos^2\delta_0$ are equal, as they are for the test machine, the value of C given by this formula is constant. If the coefficients are nearly equal, as they often are in a large generator, C is given approximately by the following expression:

$$C = \tfrac{1}{2}V^2\left[\left(\frac{1}{X''_d} - \frac{1}{X'_d}\right)\tau''_d + \left(\frac{1}{X''_q} - \frac{1}{X_q}\right)\tau''_q\right] \quad . \quad (7)$$



(a)



(b)

Fig. 13.—Variation of K and mC with frequency and load angle.

(a) Variation of K. (b) Variation of mC.
Load = 0·9 p.u.
——— Calculated curves.
Test points ○ 0·45 c/s.
× 1·65 c/s.
△ 2·50 c/s.

For the simplified machine represented by the equivalent circuit of Fig. 9, the sub-transient time-constant is

$$\tau''_d = \frac{1}{\omega r_2}\left(X_2 + \frac{X_m X_2}{X_m + X_2}\right) \quad . \quad . \quad . \quad . \quad (8)$$

Fig. 14 shows a set of values of C measured by the method of the last Section for different frequencies and two different values

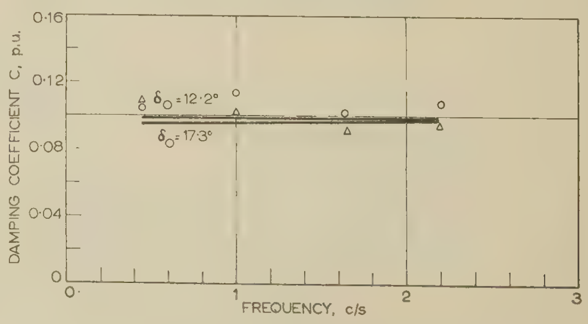


Fig. 14.—Variation of C with frequency and load angle.

——— Calculated curves.
Test points ○ $\delta_0 = 12\cdot2°$.
△ $\delta_0 = 17\cdot3°$.

δ_0. The full-line curves calculated from eqn. (5) show very tle variation either with the angle δ_0 or with the frequency.

The damping torque in a synchronous machine under various onditions is discussed more fully in Reference 3.

(5) SHORT-CIRCUIT TORQUE

(5.1) Calculation of the Electrical Short-Circuit Torque

The calculation of the transient torque following the sudden ort-circuit of a synchronous machine has been discussed by any authors.[6, 9, 16, 19–23] The electrical torque produced by the teraction of flux and current contains damped oscillatory rque components of fundamental and higher harmonic freuencies as well as unidirectional components. The peak torque ay be several times the full-load value.

The measurement of such torques or the resulting shaft rques has been attempted only occasionally.[5, 6] The application f the new torque meter to the micro-alternator has made it ossible to obtain accurate experimental results corresponding those which would be obtained on a large alternator.

The approximate formulae in eqns. (9) and (11) are given in eference 21, pp. 160 and 161. They are for short-circuits pplied at the machine terminals from no-load and are based n the assumption of negligible sub-transient saliency ($X_d'' \simeq X_q''$), condition which is very nearly satisfied by the machine tested.

Three-phase short-circuit. The expression is as follows:

$$T_e = V^2\left(\frac{F}{X_d''}\varepsilon^{-t/\tau_a}\sin\omega t + \frac{F^2 r_a}{X_d''^2} + \frac{r_d}{X_d''^2}\varepsilon^{-2t/\tau_a}\right) \quad . \quad (9)$$

$$\left.\begin{aligned} \text{here } F &= \left(1 - \frac{X_d''}{X_d'}\right)\varepsilon^{-t/\tau_d''} + \left(\frac{X_d''}{X_d'} - \frac{X_d''}{X_d}\right)\varepsilon^{-t/\tau_d'} + \frac{X_d''}{X_d} \\ r_d &= \text{Real part of } jX_d(j\omega) \end{aligned}\right\} \quad (10)$$

Eqn. (9) shows that the torque after a symmetrical shortrcuit does not depend on the instant in the cycle at which the witch closes.

Line-to-line short-circuit.—The expression is as follows:

$$\begin{aligned} {}_e = V^2\Bigg[&-\frac{F}{X_d''}\varepsilon^{-t/\tau_a}\sin\lambda\cos(\omega t + \lambda) + \frac{F^2}{2X_d''}\sin 2(\omega t + \lambda) \\ &+ \frac{F^2 r_2}{2X_d''^2} + \frac{r_d}{X_d''^2}\varepsilon^{-2t/\tau_a}\sin^2\lambda\Bigg] \end{aligned} \quad (11)$$

here

$$\left.\begin{aligned} {}^{\prime}F &= \left(1 - \frac{X_d'' + X_2}{X_d' + X_2}\right)\varepsilon^{-t/\tau_{de}''} + \left(\frac{X_d'' + X_2}{X_d' + X_2}\right. \\ &\qquad \left. - \frac{X_d'' + X_2}{X_d + X_2}\right)\varepsilon^{-t/\tau_{de}'} + \frac{X_d'' + X_2}{X_d + X_2} \\ {}''_{de} &= \frac{X_d'' + X_2}{X_d' + X_2}\frac{X_d'}{X_d''}\tau_d'' \\ {}'_{de} &= \frac{X_d' + X_2}{X_d + X_2}\frac{X_d}{X_d'}\tau_d' \end{aligned}\right\} \quad (12)$$

Eqn. (11) shows that the torque after a line-to-line shortrcuit depends on the angle λ which defines the instant of vitching. The factor F given by eqn. (12) is similar to that ven by eqn. (10), except that the constants are now those of e machine with the negative-sequence reactance X_2 in series. 'ith the assumptions made, $X_2 = X_d''$.

(5.2) Calculation of the Shaft Torque from the Electrical Torque

(5.2.1) Analysis of the Mechanical System.

The mechanical system consisting of the micro-alternator coupled to a d.c. driving motor can be represented by two rotating bodies of inertias J_1 and J_2 coupled by a flexible shaft. The instantaneous shaft torque, T_s, is related to the electrical torque by the operational relation

$$T_s = \frac{J_2}{J_1 + J_2}\frac{\omega_c^2}{p^2 + 2cp + \omega_c^2}T_e \quad . \quad . \quad . \quad (13)$$

Each component of the electrical torque can be considered separately in order to determine the corresponding component of the shaft torque. One typical component of the electrical torque may be expressed as

$$T_e = T_m\varepsilon^{-at}\sin\omega_e t \quad . \quad . \quad . \quad . \quad (14)$$

The corresponding shaft torque can be obtained by solving eqn. (13) with this value of T_e. With the conditions that both T_s and dT_s/dt are initially zero, and assuming that a and c are small compared with ω_e and ω_c, the solution is

$$\begin{aligned} T_s = T_m\frac{J_2}{J_1 + J_2}M\Bigg[&\varepsilon^{-at}\sin(\omega_e t + \phi) \\ &- \frac{\omega_e}{\omega_n}\varepsilon^{-ct}\sin(\omega_n t + \phi_n)\Bigg] \end{aligned} \quad (15)$$

where $\quad \omega_n = \sqrt{(\omega_c^2 + a^2 - 2ac)} \quad . \quad . \quad . \quad . \quad . \quad . \quad (16)$

$$n = a - c \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (17)$$

$$M = \frac{\left(\frac{\omega_n}{\omega_e}\right)^2}{\sqrt{\left\{\left[\left(\frac{\omega_n}{\omega_e}\right)^2 - 1\right]^2 + 4\left(\frac{n}{\omega_e}\right)^2\right\}}} \quad . \quad . \quad (18)$$

$$\phi = \arc\tan\frac{2\frac{n}{\omega_e}}{\left(\frac{\omega_n}{\omega_e}\right)^2 - 1} \quad . \quad . \quad . \quad . \quad . \quad . \quad (19)$$

and $\quad \phi_n = \arc\tan\dfrac{2\omega_n n}{\omega_n^2 - \omega_e^2 - 2n^2} \quad . \quad . \quad . \quad . \quad (20)$

The form of the solution is similar to the conventional form for a sustained applied oscillation. In the solution for the damped applied oscillation the modified values of natural frequency and damping factor defined by eqns. (16) and (17) are used.

A similar solution is obtained for the shaft torque due to a unidirectional component of the electrical torque:

$$T_e = T_m\varepsilon^{-at} \quad . \quad . \quad . \quad . \quad . \quad (21)$$

The corresponding shaft torque is

$$T_s = T_m\frac{J_2}{J_1 + J_2}[\varepsilon^{-at} - \varepsilon^{-ct}\sin(\omega_n t + \phi_n)] \quad . \quad (22)$$

where $\quad \phi_n = -\arc\tan\omega_n/n \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (23)$

The first term of eqn. (15) is a forced oscillation at the frequency ω_e of the electrical torque component, and the first term of eqn. (22) is a unidirectional torque. The second term in either equation is a free oscillation at the modified natural frequency ω_n of the mechanical system. The resultant shaft torque is obtained by superimposing all the components.

(5.2.2) **Resonance.**

In Fig. 15 the magnification factor, M, given by eqn. (18) is shown as a function of ω_n/ω_e for different values of n/ω_e. Resonance occurs when $\omega_n = \omega_e$, and M becomes infinite if in

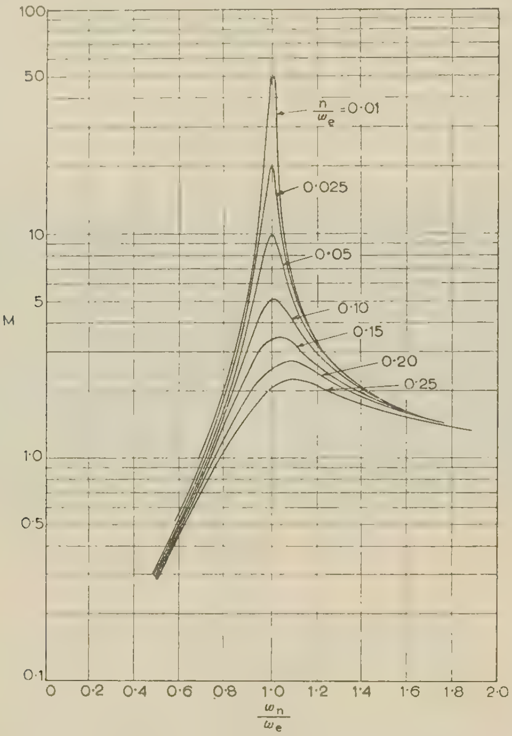


Fig. 15.—Magnification factor.

addition $n = 0$, i.e. if $a = c$. However, the shaft torque does not become infinite because of the decay of the applied oscillation.

In the limit, with $\omega_n = \omega_e$ and $c = a$, eqn. (15) reduces to

$$T_s = -T_m \frac{J_2}{J_1 + J_2} \frac{\omega_e}{2} t\varepsilon^{-ct} \cos \omega_e t \quad . \quad . \quad (24)$$

The envelope curves of this oscillatory wave are

$$\pm T_m \frac{J_2}{J_1 + J_2} \frac{\omega_e}{2} t\varepsilon^{-ct}$$

and the maximum, which occurs at $t = 1/c$, is

$$T_{s(max)} = 0 \cdot 184 \frac{J_2}{J_1 + J_2} \frac{\omega_e}{a} T_m \quad . \quad . \quad . \quad (25)$$

In Fig. 16(a) is shown the electrical torque component, with $T_m = 1$, which would resonate with the mechanical system used for the tests described in Section 5.4. The resulting shaft torque, which has a maximum value $3 \cdot 82 T_m$, is shown in Fig. 16(b).

(5.3) The Micro-Alternator and its Constants

The micro-alternator is a small model synchronous machine designed so that its resistances, inductances and other constants, when measured on a per-unit basis, are similar to those of a large generator. The micro-alternator used for the present tests is a salient-pole machine which simulates a typical hydro-electric generator. In the model machine the resistance of the field winding is higher than that required for good simulation, and hence the transient time-constant τ_d' is low. The installation includes auxiliary equipment[2] which can increase the effective time-constant, but this was not used for the present experiments.

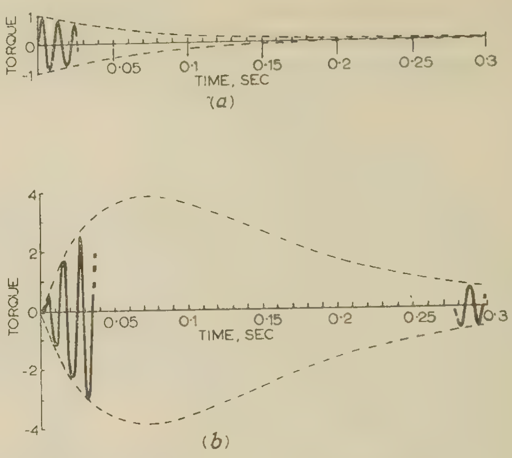


Fig. 16.—Torque curves under resonant conditions.
(a) Electrical torque.
(b) Shaft torque.

The micro-alternator is a 4-pole 3-phase 50 c/s star-connected machine rated at 230 volts, 2·25 kVA. The per-unit quantities are based on unit voltage per phase of 133 volts and unit current per phase of 5·6 amp. The parameters measured by standard test methods[24] are as follows:

$X_d = 1 \cdot 09$	$r_a = 0 \cdot 007$
$X_q = 0 \cdot 66$	$r_2 = 0 \cdot 038$
$X_d' = 0 \cdot 264$	$\tau_d' = 0 \cdot 195$ sec
$X_d'' = 0 \cdot 169$	$\tau_d'' = 0 \cdot 023$ sec
$X_q'' = 0 \cdot 164$	$\tau_a = 0 \cdot 053$ sec

The moments of inertia of the alternator and the d.c. motor were determined by a deceleration test. By taking a transient record on the torque meter after suddenly increasing the armature voltage of the motor the mechanical natural frequency was found to be 92 c/s and the time-constant of decay was 0·07 sec. The constants of the mechanical system are

$$J_2/(J_1 + J_2) = 0 \cdot 51, \ \omega_c = 578 \text{ rad/sec}, \ c = 14 \cdot 3 \text{ sec.}^{-1}$$

(5.4) Comparison of Calculations and Test Results

Oscillograms of the transient torque were taken for a number of short-circuit conditions on an unloaded machine and compared with calculated curves.

(5.4.1) **Three-Phase Short-Circuit.**

Fig. 17(a) shows the calculated electrical torque after a sudden symmetrical short-circuit at the machine terminals at rated voltage. The expression for the electrical torque calculated from eqn. (9) is as follows:

$$T_e = 5 \cdot 92 F\varepsilon^{-t/0 \cdot 053} \sin 314t + 0 \cdot 246 F^2 + 0 \cdot 48 \varepsilon^{-t/0 \cdot 026} \quad (26)$$

where

$$F = 0 \cdot 36 \varepsilon^{-t/0 \cdot 023} + 0 \cdot 485 \varepsilon^{-t/0 \cdot 195} + 0 \cdot 155$$

The unidirectional torque is relatively small and the main component is a damped oscillation at 50 c/s.

The shaft torque calculated by applying eqn. (15) to the oscillating components and eqn. (22) to the unidirectional components of the electrical torque is obtained in two parts. Fig. 17(b) shows the forced oscillation corresponding to the first terms of the equations, and Fig. 17(c) shows the free oscillation

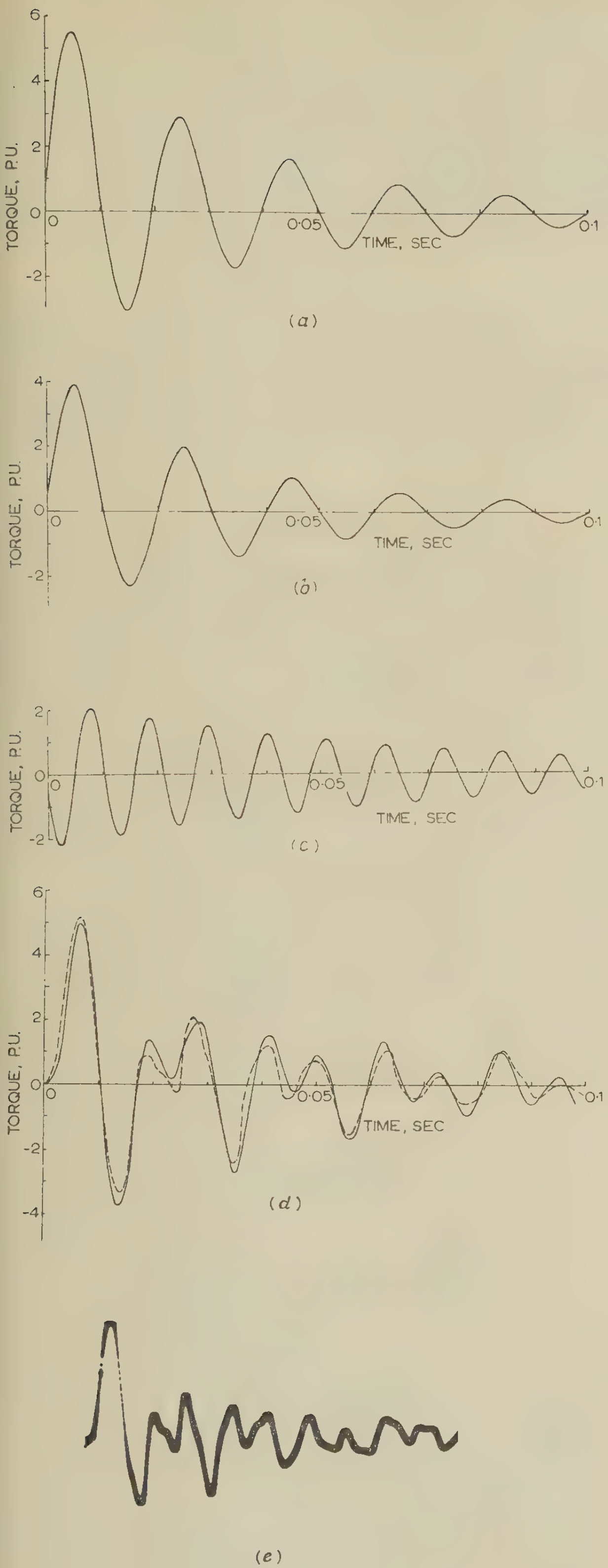


Fig. 17.—Transient torque after a 3-phase short-circuit.

(a) Electrical torque.
(b) Forced oscillation of shaft torque.
(c) Free oscillation of shaft torque.
(d) Resultant shaft torque.
——— Calculated. ---- Test.
(e) Oscillogram of shaft torque.

corresponding to the second terms. Combining these two parts gives the resultant shaft torque, which is shown by the full line in Fig. 17(*d*).

Fig. 17(*e*) is the oscillogram recorded with the torque meter. This is reproduced in Fig. 17(*d*) by the dotted line for direct comparison with the calculated curve. The measurements confirm well the accuracy of the theory.

(5.4.2) Line-to-Line Short-Circuit.

The line-to-line short-circuit torque contains a large second-harmonic component, which has a frequency near the natural frequency of 92 c/s. The tests were therefore carried out at reduced voltage to limit the peak shaft torque to a safe value.

A number of short-circuit tests was made which gave results corresponding to random values of the initial angle λ. The line-to-line voltage was also recorded, and the instant at which this was reduced to zero by the short-circuit determined the initial angle, λ, for each test.

Fig. 18(*a*) shows the calculated electrical torque curve after a

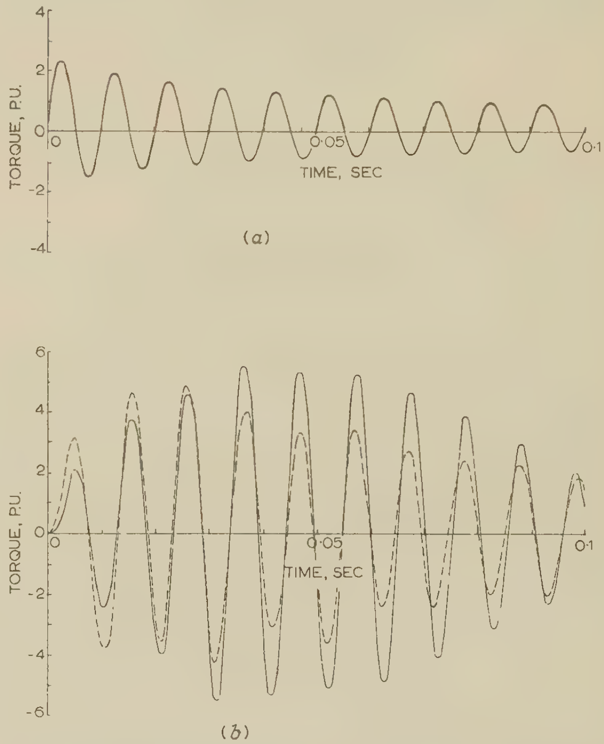


Fig. 18.—Transient torque after a line-to-line short-circuit ($\lambda = 0$).

(a) Electrical torque.
(b) Shaft torque.
——— Calculated. ---- Test.

line-to-line short-circuit at 84% of the normal voltage and with $\lambda = 0$. The expression for the electrical torque calculated from eqn. (11) is

$$T_e = 2\cdot08F^2 \sin 628t + 0\cdot4F^2 \quad . \quad . \quad . \quad . \quad . \quad (27)$$

where $$F = 0\cdot22\varepsilon^{-t/0\cdot0286} + 0\cdot51\varepsilon^{-t/0\cdot275} + 0\cdot27$$

Since the short-circuit occurred at $\lambda = 0$, the electrical torque contains no fundamental frequency component. In Fig. 18(*b*) the full line shows the calculated shaft torque, and the dotted line shows the measured torque transcribed from an oscillogram. The nature of the shaft-torque build-up resembles that obtained with exact resonance, considered analytically in Section 5.2.2.

Another test at the same reduced voltage of 84% resulted in

a line-to-line short-circuit at $\lambda = -\pi/4$. The calculated electrical torque for this condition is shown in Fig. 19(*a*). The expression derived from eqn. (11) is

$$T_e = 2\cdot95F\varepsilon^{-t/0\cdot053}\cos(314t - \pi/4) - 2\cdot08F^2\cos 628t + 0\cdot47F^2 + 0\cdot14\varepsilon^{-t/0\cdot026} \quad (28)$$

The calculated electrical torque, which is shown in Fig. 19(*a*), contains a large fundamental frequency component in addition

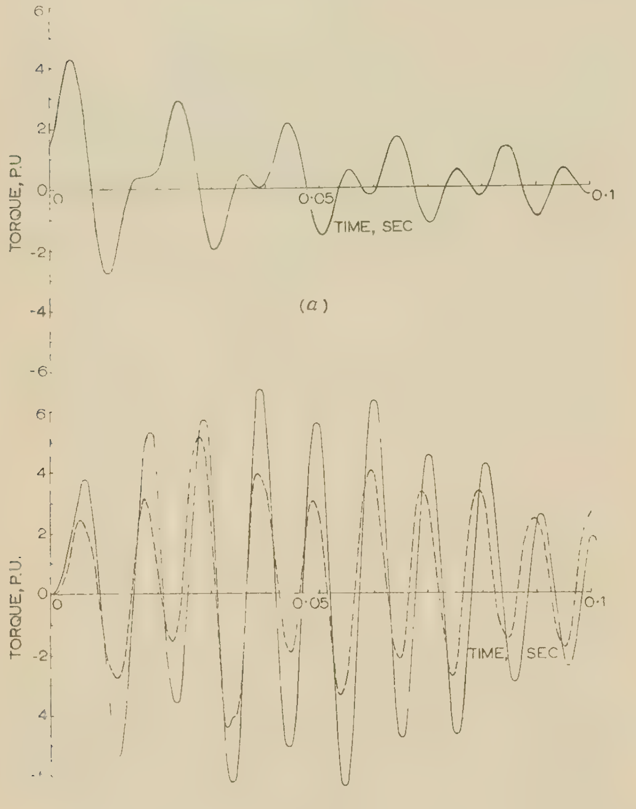


Fig. 19.—Transient torque after a line-to-line short-circuit $\left(\lambda = \frac{\pi}{4}\right)$

(*a*) Electrical torque.
(*b*) Shaft torque.
—— Calculated. ---- Test.

to the second-harmonic and unidirectional components. In Fig. 19(*b*) the full line shows the calculated shaft torque and the dotted line shows the torque obtained by measurement.

Figs. 18 and 19 show how the second-harmonic component of torque may be magnified by mechanical resonance and how excessive shaft stresses may occur if the natural frequency is too close to the frequency of an electrical torque component. The measured torques show the effect of resonance quite clearly, although the magnification is less than calculated.

(6) CONCLUSION

The experimental determination of the transient torque of a synchronous machine presented considerable difficulties even under laboratory conditions. The paper describes the development of apparatus for measuring the torque and the load angle and gives some results obtained during the course of the development. The micro-machines and their associated auxiliary equipment were not fully available at the time. The torque and load-angle meters and the complete micro-machine equipment now provide means for making a thorough study of other aspects of the transient behaviour of large synchronous machines.

(7) ACKNOWLEDGMENTS

The equipment used for the tests was provided by the Department of Scientific and Industrial Research and the Central Electricity Authority in collaboration with Electricité de France. The work was carried out in the Electrical Engineering Department of Imperial College and thanks are due to many colleagues for their assistance.

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TRANSIENT TORQUE AND LOAD ANGLE OF A SYNCHRONOUS GENERATOR FOLLOWING SEVERAL TYPES OF SYSTEM DISTURBANCE

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SUMMARY

The paper develops theoretical methods of calculating the variation torque and load angle of a synchronous machine connected to a ed supply voltage. In order to supplement and explain the results recent full-scale tests the following conditions are considered:

(*a*) Condition after a sudden short-circuit.
(*b*) Condition after switching in a reactance between the generator d the supply.
(*c*) Asynchronous operation.
(*d*) Resynchronization after asynchronous operation.

In a companion paper experimental equipment for measuring the riations of torque and load angle of a small synchronous machine is scribed. The equipment has been used to verify the theoretical sults for each of the above conditions. The machine tested was a odel alternator or 'micro-alternator' which simulates a typical ge machine. The special laboratory equipment is of great value studying in detail the factors governing the performance of large ernators.

LIST OF SYMBOLS

a, b = Damping coefficients [eqns. (38) and (59)].
$G(p)$ = Operational function [eqn. (67)].
H = Inertia constant of machine set.
i = Instantaneous current.
i_{dt}, i_{qt} = Components of axis currents [eqns. (6) and (82)].
I = Armature r.m.s. current.
J_1, J_2 = Moments of inertia of alternator and prime mover.
$, L_f, L_{kd}, L_{kq}$ = Leakage inductances.
L_e = External inductance.
L_{md}, L_{mq} = Magnetizing inductances.
p = Heaviside operator, d/dt.
P = Steady power output.
r = Winding resistance.
R_{d1}, R_{d2}, R_q = Derived resistances [eqns. (5) and (82)].
s = Slip.
T_e = Electrical torque of alternator.
T_m = Prime-mover torque.
T_s = Shaft torque.
T_u = Unidirectional torque.
u = Instantaneous speed, rad/s.
v = Instantaneous voltage.
V, V_m = R.M.S. and maximum voltage of fixed supply.
V_o = Voltage behind synchronous reactance.
V_q' = Voltage behind transient reactance.
$X_d(p), X_q(p)$ = Operational impedances [eqns. (66)].
X_d, X_q = Synchronous reactances.
X_d' = Transient reactance.
X_d'', X_q'' = Sub-transient reactances.
X_e = External reactance.
Y_a, Y_b, Y_c, Y_d = Real and imaginary components of admittances [eqns. (46)].
$\alpha = 1/\tau_a$ [eqn. (4)].
δ = Instantaneous load angle.
τ_a = Armature time-constant.
τ_d' = Short-circuit transient time-constant.
τ_{do}' = Open-circuit transient time-constant.
τ_d'', τ_q'' = Short-circuit sub-transient time-constants.
τ_{do}'', τ_{qo}'' = Open-circuit sub-transient time-constants.
τ_{kd} = Damper winding time-constant.
ψ = Armature flux linkage.
ω = Synchronous speed.

Suffixes.

a, b, c = Armature phases.
d = Direct axis.
e = Parameter of modified alternator (Section 4.1).
f = Field winding.
kd, kq = Damper windings.
q = Quadrature axis.

Written contributions on papers published without being read at meetings are ted for consideration with a view to publication.
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(1) INTRODUCTION

Full-scale tests performed in recent years by the Central Electricity Authority[1, 2] have provided very valuable information about the behaviour of an alternator after a short-circuit, after a fault on the supply system, or when the alternator runs temporarily out of synchronism. It is difficult, however, to carry out the investigation on the large-scale equipment in sufficient detail to obtain a full theoretical explanation of these phenomena.

The 'micro-machine' equipment[3] in the laboratories at Imperial College has been used to study some of these problems in more detail. These small model machines can be tested more fully and their basic parameters can be measured more precisely than is possible with the large alternators of a power system. It is of particular value that the transient torque can be readily measured, since this is the most important quantity determining the behaviour of the machine.[4]

The general differential equations of the synchronous machine, formulated by R. H. Park in 1929,[5] provide a means of investigating any manner of operation of the machine. A full theoretical treatment, based on Park's equations, is given in the present paper for several types of disturbance. There is a good deal of previously published work on the subject, but many of the derivations and some of the results are new. Each of the formulae derived theoretically is verified by calculations and tests on a micro-alternator.

The problems, all of which relate to conditions where the connections are symmetrical between the phases, are described under four headings.

(*a*) *Short-Circuit Torque.*—Concordia has derived an expression for the torque following a 3-phase short-circuit on an unloaded alternator, including terms for the unidirectional torque component.[6] A new simplified and more rigorous derivation is given below, and the method is extended to the

case of an initially loaded machine. Tests on large alternators have shown that, after a short-circuit on a loaded machine, there is a temporary dip in speed before the main rise of speed. The investigation provides an explanation of this occurrence.

(*b*) *Swing Curves following an Increase of Reactance between the Alternator and a Fixed Supply* (*Infinite Busbar*).—Several methods of calculating the swing curves are given by Crary,[7] ranging from the simple method based on constant flux linkage and no damping, to an accurate but laborious method described in a paper by Crary and Waring.[8] A new simplified derivation of all these methods is given below, and it is shown how each of the formulae can be derived in succession by making certain simplifying assumptions. A clearer understanding of the part played by the damper winding and the variation of field flux linkage is therefore obtained.

(*c*) *Asynchronous Operation.*—A method of calculating the currents and torque in a synchronous motor running at a constant speed away from synchronism is given by Linville.[9] The method is extended in the present paper to determine approximately the pulsations of torque and slip occurring in an alternator running continuously out of step.

(*d*) *Resynchronization.*—The slip pulsation during out-of-step operation is used to arrive at an approximate criterion to determine the conditions under which an alternator can resynchronize.

The general differential equations of the synchronous machine, which are used as the starting-point for the derivations explained in the following Sections, are stated in Section 10.1. The machine is assumed to be 'ideal' as defined by Park,[10] and is further simplified by representing the damper winding by a single coil on each axis (see Fig. 1). The form of the equations and

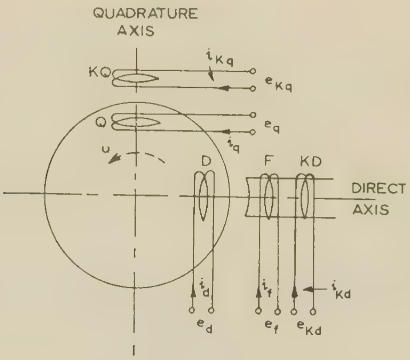


Fig. 1.—Two-axis representation of a synchronous machine.

the notation used are based on a book by one of the authors,[11] where more detailed explanations of many of the methods may be found. The operational solutions are obtained by means of the Heaviside standard forms listed in Section 10.2.

(2) THE EXPERIMENTAL MACHINES AND ASSOCIATED EQUIPMENT

The main machine used in the experimental work recorded in the paper is a 'micro-alternator' which simulates a large generator. The particular machine used has a short-circuit ratio of approximately unity, which is a typical figure for a large waterwheel alternator. It is direct coupled to a d.c. machine which serves as a prime mover. A torque coupling is mounted between the two machines and a small 2-phase tachogenerator is coupled to the alternator at the non-driving end. The torque coupling, the tachogenerator, and the auxiliary equipment used to measure the instantaneous torque and load angle under transient conditions are described in a companion paper.[4] Fc all the tests a filter was used with the torque meter to eliminat oscillations at frequencies of 25 c/s and over.

The parameters of the micro-alternator, measured on a pe unit basis, are of the same order of magnitude as those of typical large machine, except that the field resistance is abou five times too high. In order to obtain a correct simulation the machine operates in conjunction with an external electroni device, known as a time-constant regulator, which introduces negative resistance into the field circuit. In this way the effectiv field resistance can be adjusted to any required value. The se is also provided with an adjustable flywheel in order to obtai a suitable inertia constant.

The d.c. machine is supplied at constant voltage and i separately excited. It has a large resistance in the armatur circuit in order to obtain a torque/speed characteristic of th same type as that of a turbine. During transient conditio the speed varies by a few per cent. In a typical turbine a 1 rise in speed causes a 1% drop in torque, but in the d.c. machi it was not feasible to reduce the change of torque below 4 (see Fig. 2). The resulting effect was small and was fu allowed for in the calculations.

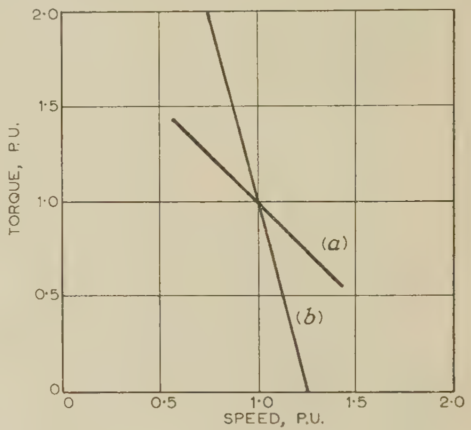


Fig. 2.—Torque/speed characteristics.
(*a*) Typical turbine.
(*b*) D.C. motor with external resistance.

The micro-alternator is a 4-pole 3-phase 50 c/s star-connecte machine rated at 220 volts, 3 amp, 1·145 kVA.

The per-unit quantities are based on

Unit voltage per phase	=	127 volts.
Unit current per phase	=	3·0 amp.
Unit field current	=	0·396 amp.
Unit field resistance	=	7 150 ohms.

The parameters measured by standard test methods are

$X_d = 1\cdot 15$	$\tau_a = 0\cdot 065$
$X_q = 0\cdot 51$	$\tau'_d = 0\cdot 21$
$X'_d = 0\cdot 18$	$\tau''_d = 0\cdot 02$
$X''_d = 0\cdot 09$	$\tau''_q = 0\cdot 028$
$X''_q = 0\cdot 09$	$\tau'_{do} = 1\cdot 33$
$r_a = 0\cdot 006$	$\tau''_{do} = 0\cdot 036$
$r_f = 0\cdot 0028$	$\tau''_{qo} = 0\cdot 15$

X_d and X_q are unsaturated values. r_f can be reduced to an desired value by the time-constant regulator and τ'_d and τ'_{do} ar then increased in the inverse ratio.

(3) THREE-PHASE SHORT-CIRCUIT TORQUE

(3.1) Mathematical Derivation

efore the short-circuit the alternator runs at the synchronous ed ω and is loaded so that the steady currents are i_{do}, i_{qo}, flux linkages ψ_{do}, ψ_{qo}, and the axis voltages v_{do}, v_{qo}. The d voltage, v_f, is unaffected by the short-circuit and it is assumed t the speed remains constant at the value ω. With this imption, eqns. (61) and (65), which relate the instantaneous ntities, are linear differential equations and therefore hold for the superimposed changes, indicated in eqns. (1) and (2) symbols with dashes.

$$\left.\begin{aligned} -v_{do}1 &= p\psi_d' + \omega\psi_q' + r_a i_d' \\ -v_{qo}1 &= -\omega\psi_d' + p\psi_q' + r_a i_q' \end{aligned}\right\} \quad . \quad . \quad . \quad (1)$$

ere 1 is the Heaviside unit function.

$$\omega\psi_d' = X_d(p)i_d', \quad \omega\psi_q' = X_q(p)i_q' \quad . \quad . \quad . \quad (2)$$

he required currents and flux linkages after the short-circuit each equal to the sum of the steady value, denoted by a symbol n suffix o, and the superimposed change, obtained by solving s. (1) and (2). They are given by the operational expressions eqns. (3), in which the quadratic factor $p^2 + 2\alpha p + \omega^2$ is ained as a result of an approximation based on the fact that s small. (For further explanation, see Reference 11.)

$$\left.\begin{aligned} i_d &= i_{do} + \frac{\omega^2}{p^2 + 2\alpha p + \omega^2}\frac{1}{X_d(p)} \left[v_{qo} - \frac{p}{\omega}v_{do} - \frac{r_a}{X_q(p)}v_{do}\right] \\ i_q &= i_{qo} - \frac{\omega^2}{p^2 + 2\alpha p + \omega^2}\frac{1}{X_q(p)} \left[v_{do} + \frac{p}{\omega}v_{qo} + \frac{r_a}{X_d(p)}v_{qo}\right] \\ \psi_d &= \psi_{do} + \frac{\omega}{p^2 + 2\alpha p + \omega^2}\left[v_{qo} - \frac{p}{\omega}v_{do} - \frac{r_a}{X_q(p)}v_{do}\right] \\ \psi_q &= \psi_{qo} - \frac{\omega}{p^2 + 2\alpha p + \omega^2}\left[v_{do} + \frac{p}{\omega}v_{qo} + \frac{r_a}{X_d(p)}v_{qo}\right] \end{aligned}\right\} \quad (3)$$

re

$$\alpha = \frac{\omega r_a}{2}\left(\frac{1}{X_d''} + \frac{1}{X_q''}\right) = \frac{1}{\tau_a} \quad . \quad . \quad . \quad . \quad (4)$$

qns. (6) give the currents and flux linkages as functions of . The solution of eqns. (3) is obtained by using the partial tions of eqns. (68) and (69) and the Heaviside standard forms eqns. (78). In the solution the following new symbols, ned in eqns. (82), are introduced:

$_t$, i_{qt} are decaying exponential components of the axis ents.

$_{d1}$, R_{d2}, R_q are quantities which depend on the damper and winding resistances. They can be derived from the opera- al impedances as follows:

$$\left.\begin{aligned} R_{d1} + R_{d2} &= \mathscr{R}[jX_d(j\omega)] \\ R_q &= \mathscr{R}[jX_q(j\omega)] \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad (5)$$

qns. (6) are approximate expressions obtained by neglecting erms containing squares or products of the small quantities , R_{d1}, R_{d2}, R_q.

$$\left.\begin{aligned} i_d = i_{do} + i_{dt} &- \frac{r_a v_{do}}{X_d'' X_q''} + \left(\frac{R_{d1}}{X_d'^2}\varepsilon^{-t/\tau_d'} + \frac{R_{d2}}{X_d''^2}\varepsilon^{-t/\tau_d''}\right)v_{do} \\ &- \left[\frac{v_{do}}{X_d''} + \frac{\alpha}{\omega}\frac{v_{qo}}{X_d''} - \left(\frac{R_{d1}}{X_d'^2} + \frac{R_{d2}}{X_d''^2}\right)v_{qo}\right]\varepsilon^{-\alpha t}\sin\omega t \\ &- \left[\frac{v_{qo}}{X_d''} - \frac{r_a v_{do}}{X_d'' X_q''} + \left(\frac{R_{d1}}{X_d'^2} + \frac{R_{d2}}{X_d''^2}\right)v_{do}\right]\varepsilon^{-\alpha t}\cos\omega t \\ i_q = i_{qo} - i_{qt} &- \frac{r_a v_{qo}}{X_d'' X_q''} + \frac{R_q}{X_q''^2}\varepsilon^{-t/\tau_q''}v_{qo} \\ &- \left(\frac{v_{qo}}{X_q''} - \frac{\alpha}{\omega}\frac{v_{do}}{X_q''} + \frac{R_q}{X_q''^2}v_{do}\right)\varepsilon^{-\alpha t}\sin\omega t \\ &+ \left(\frac{v_{do}}{X_q''} + \frac{r_a v_{qo}}{X_d'' X_q''} - \frac{R_q}{X_q''^2}v_{qo}\right)\varepsilon^{-\alpha t}\cos\omega t \\ \psi_d = \frac{1}{\omega}\Bigg[&(i_{qo} - i_{qt})r_a - \left(v_{do} + \frac{\alpha}{\omega}v_{qo}\right)\varepsilon^{-\alpha t}\sin\omega t \\ &- \left(v_{qo} - \frac{r_a v_{do}}{X_q''}\right)\varepsilon^{-\alpha t}\cos\omega t\Bigg] \\ \psi_q = -\frac{1}{\omega}\Bigg[&(i_{do} + i_{dt})r_a + \left(v_{qo} - \frac{\alpha}{\omega}v_{do}\right)\varepsilon^{-\alpha t}\sin\omega t \\ &- \left(v_{do} + \frac{r_a v_{qo}}{X_d''}\right)\varepsilon^{-\alpha t}\cos\omega t\Bigg] \end{aligned}\right\} \quad (6)$$

The torque is now calculated by substituting the values of i_d, i_q, ψ_d and ψ_q from eqns. (6) in eqn. (64). The resulting torque contains, on the one hand, oscillating terms at angular frequencies ω and 2ω and, on the other hand, unidirectional terms. The unidirectional terms, which depend on the resistances, are of smaller magnitude than the oscillating terms. In the derivation of eqn. (7), all terms containing resistances have been neglected in the oscillating part, and all terms containing squares or products of resistances have been neglected in the unidirectional part.

$$\left.\begin{aligned} T_e = \frac{1}{2}\Bigg\{&[v_{qo}(i_{do} + i_{dt}) - v_{do}(i_{qo} - i_{qt})]\varepsilon^{-\alpha t}\sin\omega t \\ &- [v_{do}(i_{do} + i_{dt}) + v_{qo}(i_{qo} - i_{qt})]\varepsilon^{-\alpha t}\cos\omega t \\ &+ \frac{1}{2}(v_{qo}^2 - v_{do}^2)\left(\frac{1}{X_q''} - \frac{1}{X_d''}\right)\varepsilon^{-2\alpha t}\sin 2\omega t \\ &- v_{qo}v_{do}\left(\frac{1}{X_q''} - \frac{1}{X_d''}\right)\varepsilon^{-2\alpha t}\cos 2\omega t \\ &+ r_a[(i_{do} + i_{dt})^2 + (i_{qo} - i_{qt})^2] \\ &+ \frac{1}{2}(v_{qo}^2 + v_{do}^2)\left(\frac{R_{d1}}{X_d'^2} + \frac{R_{d2}}{X_d''^2} + \frac{R_q}{X_q''^2}\right)\varepsilon^{-2\alpha t} \\ &+ \frac{1}{4}(v_{qo}^2 + v_{do}^2)\left(\frac{1}{X_d''} - \frac{1}{X_q''}\right)^2 r_a\varepsilon^{-2\alpha t}\Bigg\} \end{aligned}\right\} \quad (7)$$

(3.2) Short-Circuit Torque of an Unloaded Alternator

For an unloaded alternator, eqn. (7) is simplified by substituting $i_{do} = i_{qo} = 0$, $v_{do} = 0$:

$$T_e = \frac{1}{2}\left[v_{qo} i_{dt} \varepsilon^{-\alpha t} \sin \omega t + \frac{1}{2} v_{qo}^2 \left(\frac{1}{X_q''} - \frac{1}{X_d''}\right) \varepsilon^{-2\alpha t} \sin 2\omega t + r_a i_{dt}^2 + \frac{1}{2} v_{qo}^2 \left(\frac{R_{d1}}{X_d'^2} + \frac{R_{d2}}{X_d''^2} + \frac{R_q}{X_q''^2}\right) \varepsilon^{-2\alpha t} + \frac{1}{4} v_{qo}^2 \left(\frac{1}{X_q''} - \frac{1}{X_d''}\right)^2 r_a \varepsilon^{-2\alpha t} \right] \quad (8)$$

The expression corresponds to that given in Reference 4, but contains some additional terms of small magnitude.

(3.3) The Unidirectional Components of the Short-circuit Torque

The unidirectional torque arises because of the ohmic losses in the armature circuit and in the field and damper circuits. It may be divided into three components.

(a) *First Unidirectional Component.*

$$T_{u1} = \tfrac{1}{2} r_a [(i_{do} + i_{dt})^2 + (i_{qo} - i_{qt})^2] = r_a I_1^2 \quad . \quad . \quad . \quad (9)$$

I_1 is the r.m.s. value of the fundamental-frequency stator current and hence T_{u1} represents the armature-winding copper loss due to this current.

(b) *Second Unidirectional Component.*

$$T_{u2} = \frac{1}{4}(v_{qo}^2 + v_{do}^2)\left(\frac{R_{d1}}{X_d'^2} + \frac{R_{d2}}{X_d''^2} + \frac{R_q}{X_q''^2}\right)\varepsilon^{-2\alpha t} = \frac{1}{2} V^2 \left(\frac{R_{d1}}{X_d'^2} + \frac{R_{d2}}{X_d''^2} + \frac{R_q}{X_q''^2}\right)\varepsilon^{-2\alpha t} \quad . \quad . \quad . \quad (10)$$

The resistance R_{d1}, R_{d2}, R_q are derived from the real parts of the operational impedances, as in eqns. (5). The reactances X_d', X_d'', X_q'', are corresponding imaginary parts, which are much greater than the resistances and may therefore be regarded as impedances. V is the r.m.s. phase voltage. It follows that T_{u2} represents the copper loss due to the fundamental-frequency induced currents in the field and damper circuits.

(c) *Third Unidirectional Component.*

$$T_{u3} = \frac{1}{4} V^2 \left(\frac{1}{X_d''} - \frac{1}{X_q''}\right)^2 r_a \varepsilon^{-2\alpha t} \quad . \quad . \quad . \quad (11)$$

T_{u3} is due to the sub-transient saliency, which gives rise to an additional loss in the armature circuit. It can generally be neglected.

(3.4) Comparison of Calculations and Test Results

(3.4.1) Short-Circuit of a Loaded Alternator.

Before the short-circuit the alternator was driven by the d.c. motor and supplied power to the fixed supply. After the short-circuit the sudden transient torque produced by the alternator temporarily exceeded the torque of the driving motor, resulting in a drop in speed. Subsequently, when the alternator torque decayed, the machines accelerated above synchronous speed because of the d.c. motor torque.

Fig. 3 shows the main connections of the machines and the measuring equipment. A protective impedance was connected between the alternator and the fixed supply in order to limit the fault current taken from the supply. During the original steady condition the load angle δ_0 is measured in relation to the

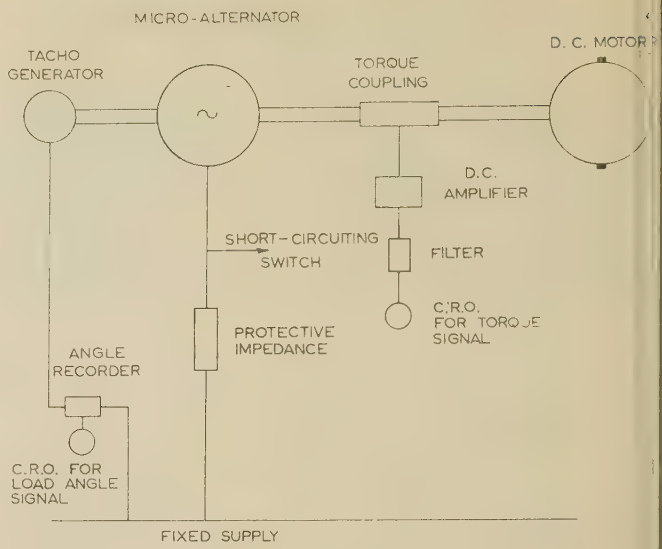


Fig. 3.—Connections for the short-circuit test.

reference voltage at the machine terminals, but after the short-circuit this voltage is zero and there is no load angle in the ordinary sense. The load-angle meter was used to measure the angle δ of the rotor in relation to the synchronous reference voltage taken from the fixed supply. For this purpose the meter is merely a convenient means of determining the absolute angular position and speed of the rotor.

The constants of the machine are those given in Section [illegible] except that the effective transient time-constant, τ_d', is increased to 0·92 sec by the time-constant regulator already described. The inertia constant of the set is $H = 5{\cdot}4$ sec. In the original steady condition the per-unit values of the quantities were

$P = 1{\cdot}0$	$v_{do} = -0{\cdot}74$
$V = 1{\cdot}05$	$v_{qo} = 1{\cdot}29$
$I = 1{\cdot}1$	$i_{do} = 1{\cdot}27$
$\cos\phi = 0{\cdot}87$ lag	$i_{qo} = -0{\cdot}905$
$\delta_0 = -30°$	

The unidirectional torque T_u was calculated from eqns. (9) and (10), and the d.c. motor torque T_m was taken equal to P. The angle δ was then calculated from the differential equation

$$\frac{2H}{\omega}\frac{d^2\delta}{dt^2} = -(T_m - T_u) \quad . \quad . \quad . \quad . \quad (12)$$

given that $\delta = \delta_0$, $\dfrac{d\delta}{dt} = 0$, at $t = 0$.

The following expressions were obtained:

$$T_{u1} = 0{\cdot}037 + 0{\cdot}097\varepsilon^{-1\cdot09t} + 0{\cdot}120\varepsilon^{-2\cdot18t} + 0{\cdot}102\varepsilon^{-36t} + 0{\cdot}380\varepsilon^{-50t} + 0{\cdot}156\varepsilon^{-72t} + 0{\cdot}156\varepsilon^{-100t}$$

$$T_{u2} = 1{\cdot}33\varepsilon^{-30t}$$

$$T_m = 1{\cdot}0$$

$$\delta = -802t^2 + 337{\cdot}7t - 182{\cdot}1 + 136\varepsilon^{-1\cdot09t} + 42\varepsilon^{-2\cdot18t} + 0{\cdot}13\varepsilon^{-36t} + 0{\cdot}25\varepsilon^{-50t} + 0{\cdot}05\varepsilon^{-72t} + 0{\cdot}03\varepsilon^{-100t} + 2{\cdot}47\varepsilon^{-30t} - 30$$

In Fig. 4 the dotted curve is the measured angle and curve (a) (full line) is the angle calculated from the above expression.

The dip in the calculated curve is considerably smaller than that in the measured curve. It is evident that the calculation does not allow for all the losses occurring after the short-circuit

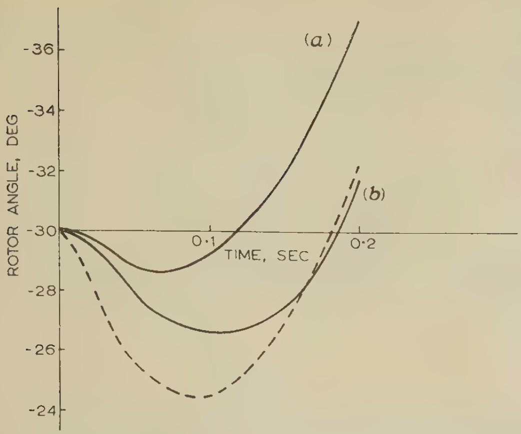


Fig. 4.—Variation of rotor angle after short-circuiting a loaded alternator.

(a) Calculated.
(b) Calculated with allowance for stray loss.
---- Test curve.

particular, the damper losses due to currents at supply fre-ency are increased because of eddy currents in the bars and he core. Thus the torque component, T_{u2}, which plays the gest part in producing the dip in the curve, is increased. In er to show the effect of such losses, curve (b) has been culated with T_{u2} increased by 50%.

The curves of Fig. 4 do not give an accurate quantitative ck, but they suffice to explain how the dip in the curve is sed by losses due to the short-circuit currents.

.2) Short-Circuit of an Unloaded Alternator.

ome further tests were made with the synchronous machine oaded before the short-circuit. The micro-alternator ran as ynchronous motor on no-load and the d.c. machine was xcited and disconnected from the supply. Under this con-on the speed fell continuously after the short-circuit.

f there were no friction the calculated expressions for torque angle would be as follows:

$$T_{u1} = 0\cdot0065 + 0\cdot065\varepsilon^{-1.09t} + 0\cdot156\varepsilon^{-2.18t} + 0\cdot40\varepsilon^{-50t}$$
$$T_{u2} = 1\cdot33\varepsilon^{-30t}$$
$$T_m = 0$$
$$\delta = 5\cdot41t^2 + 308\cdot8t - 148\cdot7 + 91\cdot1\varepsilon^{-1.09t} + 54\cdot8\varepsilon^{-2.18t} + 2\cdot46\varepsilon^{-30t}$$

n Fig. 5, curve (a) shows the angle calculated from the ve expression and (b) is the modified curve when T_{u2} is eased by 50%. The effect of increasing T_{u2} becomes less ceable after a longer time interval.

he dotted curves show the test results. Curve (c) shows variation of the angle after the short-circuit and (d) shows angle measured on a deceleration test when the set slows n owing to friction only. Curve (e) shows the difference, ch depends on the unidirectional short-circuit torque eloped in the synchronous machine.

direct measurement of the torque in the shaft during this was made by means of the torque meter. A filter was used liminate most of the large alternating component of the t-circuit torque, and the electrical torque T_e was deduced n the shaft torque T_s by the relation

$$T_s = T_e\frac{J_2}{J_1 + J_2} \quad . \quad . \quad . \quad . \quad . \quad . \quad (13)$$

qn. (13) is approximately true for slowly varying torques use the natural frequency is high, although it does not correctly allow for the effect of friction. In Fig. 6, (a) shows the torque T_e deduced directly from the oscillogram, using eqn. (13). It contains a small ripple and, moreover, does not correctly record the initial part of the torque curve. Curve (b) is the undirectional torque estimated from (a). The full line shows the calculated unidirectional torque. As a further check, the torque was deduced from the measured angle [Fig. 5, curve (e)] by a double differentiation, using the method of finite

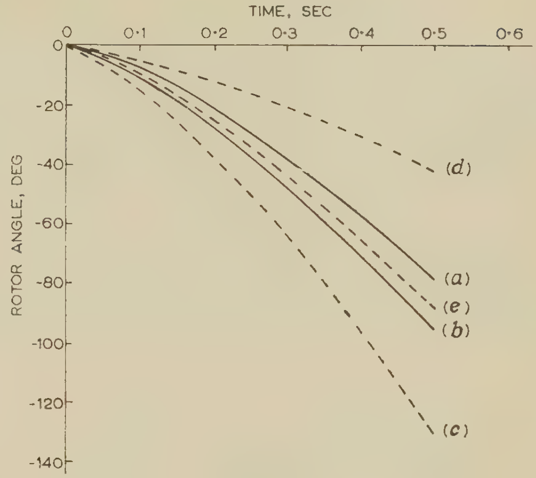


Fig. 5.—Variation of rotor angle after short-circuiting an unloaded alternator.

(a) Calculated.
(b) Calculated with allowance for stray loss.
(c) Test curve after short-circuit.
(d) Test curve on open-circuit.
(e) Difference between (c) and (d).

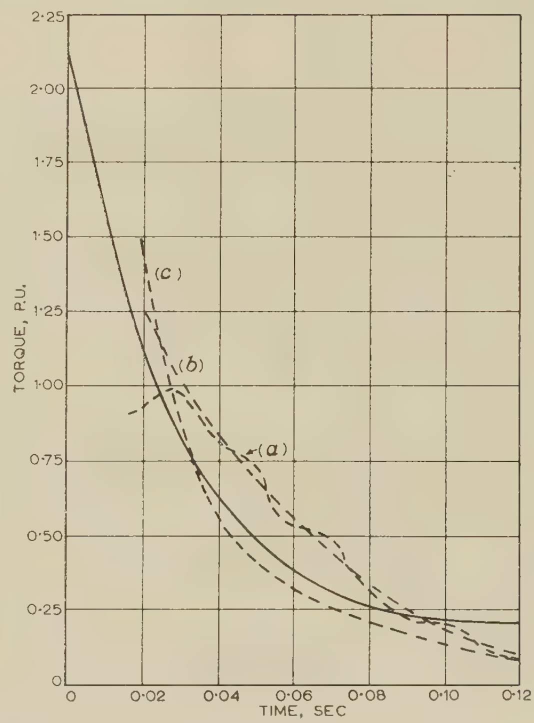


Fig. 6.—Variation of torque after short-circuiting an unloaded alternator.

—— Calculated.
(a) Deduced from oscillogram of shaft torque.
(b) Smooth curve estimated from (a).
(c) Deduced from rotor angle [curve (e) of Fig. 5].

differences. The result of this calculation is shown in (*c*) of Fig. 6.

The two methods of determining the torque from the test results provide an approximate confirmation of the calculation, although the accuracy of both methods is poor.

(4) SWING CURVES FOLLOWING A CHANGE OF REACTANCE

(4.1) Operational Expressions for the Axis Currents

A 3-phase alternator is supplying power to a fixed supply, as shown in Fig. 7, when a reactance X_e is suddenly inserted in each phase by opening the switches S. After a time the machine

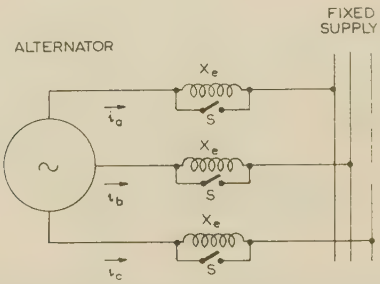


Fig. 7.—Connections of an alternator with an external reactance.

may either settle down to a new condition of synchronous operation or it may lose synchronism and operate asynchronously above synchronous speed. In order to study the condition fully it is necessary to determine the performance over a considerable period of time. This Section gives a method of calculating the torque and the load angle of the machine after the disturbance.

The speed, u, is a variable in the machine equations (61), which are inherently non-linear and can therefore only be solved by a step-by-step computation. The method used is to rearrange and simplify the equations, as explained in Section 10.1.3 so that they include the load angle, δ, as a variable instead of u. For slow transients they simplify to the approximate equations (73). If now δ were a known function of time, the currents and flux linkages, and hence the torque, could be calculated by solving a set of linear equations in which the applied voltages depend on δ. However, since δ is not a known function of time, it is necessary to formulate a general expression for the electrical torque, T_e, as a function of δ and use the expression to solve the dynamical equations of motion of the machine rotor by a step-by-step method. By this means both T_e and δ can be determined as functions of time.

Consider first the direct-axis equations (62) with the value of ψ_d inserted from eqn. (73). These equations apply to the steady condition before the switch is opened because the machine is connected directly to the fixed supply. In eqn. (14) all the terms are included, in spite of the fact that i_{do} and i_{fo} are constant and i_{kdo} is zero, in order to show more clearly the later working.

$$\left.\begin{aligned} -\frac{V_m}{\omega}\cos\delta_0 &= L_{md}i_{fo} + L_{md}i_{kdo} + (L_{md} + L_a)i_{do} \\ v_f &= [r_f + (L_{md} + L_f)p]i_{fo} + L_{md}pi_{kdo} + L_{md}pi_{do} \\ 0 &= L_{md}pi_{fo} + [r_{kd} + (L_{md} + L_{kd})p]i_{kdo} \\ &\qquad + L_{md}pi_{do} \end{aligned}\right\} \quad (14)$$

After the switch is opened the inductance increases by an amount L_e. The combination of alternator and inductance can be treated as a modified alternator having a leakage reactance $X_a + X_e = \omega(L_a + L_e)$. The field voltage is unchanged. The following equations apply to the modified alternator connected to the fixed supply:

$$\left.\begin{aligned} -\frac{V_m}{\omega}\cos\delta &= L_{md}i_f + L_{md}i_{kd} + (L_{md} + L_a + L_e)i_d \\ v_f &= [r_f + (L_{md} + L_f)p]i_f + L_{md}pi_{kd} + L_{md}pi_d \\ 0 &= L_{md}pi_f + [r_{kd} + (L_{md} + L_{kd})p]i_{kd} + L_{md}pi_d \end{aligned}\right\} \quad (15)$$

The first of eqns. (14) can be rearranged as follows:

$$-\frac{V_m}{\omega}\cos\delta_0 + L_e i_{do} = L_{md}i_{fo} + L_{md}i_{kdo} + (L_{md} + L_a + L_e)i_{do} \quad . \quad . \quad . \quad . \quad (16)$$

In each of eqns. (15) and (16) the term on the left-hand side can be regarded as an impressed voltage which changes suddenly at $t = 0$. Hence the superimposed changes of current, denoted by symbols with dashes, are determined by the equations obtained by subtracting eqns. (14) and (16) from (15):

$$\left.\begin{aligned} -\left[\frac{V_m}{\omega}(\cos\delta - \cos\delta_0) + L_e i_{do}\right]1 & \\ = L_{md}i'_f + L_{md}i'_{kd} &+ (L_{md} + L_a + L_e)i'_d \\ 0 = [r_f + (L_{md} + L_f)p]i'_f &+ L_{md}pi'_{kd} + L_{md}pi'_d \\ 0 = L_{md}pi'_f + [r_{kd} &+ (L_{md} + L_{kd})p]i'_{kd} + L_{md}pi'_d \end{aligned}\right\} \quad (17)$$

The currents i'_f and i'_{kd} are now eliminated from eqns. (17) by the method used for obtaining the first line of eqns. (65) from eqns. (62). In the present instance the field voltage is zero. In eqn. (18) the operational impedance $X_{de}(p)$ is that of the modified alternator:

$$-\left[\frac{V_m}{\omega}(\cos\delta - \cos\delta_0) + L_e i_{do}\right]1 = \frac{X_{de}(p)}{\omega}i'_d \quad . \quad (18)$$

The total current i_d is obtained by adding i_{do} to the value of i'_d given by eqn. (18). The expression for i_q is obtained in a similar manner:

$$\left.\begin{aligned} i_d &= i_{do} - \frac{1}{X_{de}(p)}[V_m(\cos\delta - \cos\delta_0) + X_e i_{do}]1 \\ i_q &= i_{qo} + \frac{1}{X_{qe}(p)}[V_m(\sin\delta - \sin\delta_0) - X_e i_{qo}]1 \end{aligned}\right\} \quad (19)$$

Eqns. (19) are used in the following Sections to calculate the electrical torque developed. The additional suffix e is used to indicate the modified value of any reactance or time-constant of the alternator. Thus, for example,

$$X_{de} = (X_d + X_e), \qquad \tau'_{de} = \tau'_{do}\frac{X'_{de}}{X_{de}} \quad . \quad . \quad . \quad (20)$$

(4.2) Step-by-Step Calculation of Torque and Load Angle

For the modified alternator the flux linkages are given by eqns. (73) and the currents by eqns. (19). The electrical torque is obtained by substituting these values in eqn. (64).

$$T_e = -\frac{V_m}{2}(i_d\sin\delta + i_q\cos\delta) \quad . \quad . \quad . \quad (21)$$

When the machine is generating, mechanical power passes to it from the prime mover, so that T_e has a positive value. The load angle δ, on the other hand, is a negative quantity because the rotor runs ahead of the reference position determined by the supply voltage. For the condition considered, δ is measured in relation to the supply voltage, not the machine terminal

age; i.e. it is the load angle of the modified alternator, in ch the external reactance has been included.

he equation of motion is eqn. (12), in which T_e is known as nction of δ and T_m as a function of speed. The equations then be solved by a step-by-step method.

) Accurate Calculation of the Torque (Crary and Waring's Method)

he operational expressions of eqns. (19) can be evaluated by ressing $1/X_{de}(p)$ and $1/X_{qe}(p)$ as sums of partial fractions lar to those given in eqns. (68) and (69), and using the dard form of eqn. (79):

$$= i_{do} - \frac{V_m}{X_{de}}(\cos\delta - \cos\delta_0)$$
$$- X_e i_{do}\left[\frac{1}{X_{de}} + \left(\frac{1}{X'_{de}} - \frac{1}{X_{de}}\right)\varepsilon^{-t/\tau'_{de}} + \left(\frac{1}{X''_{de}} - \frac{1}{X'_{de}}\right)\varepsilon^{-t/\tau''_{de}}\right]$$
$$- V_m\left(\frac{1}{X'_{de}} - \frac{1}{X_{de}}\right)\sum_{n=1}^{\infty}\varepsilon^{-(t-n\Delta t)/\tau'_{de}}\cos\delta(n\Delta t)$$
$$- V_m\left(\frac{1}{X''_{de}} - \frac{1}{X'_{de}}\right)\sum_{n=1}^{\infty}\varepsilon^{-(t-n\Delta t)/\tau''_{de}}\cos\delta(n\Delta t) \quad . \quad . \quad (22)$$

$$= i_{qo} + \frac{V_m}{X_{qe}}(\sin\delta - \sin\delta_0)$$
$$- X_e i_{qo}\left[\frac{1}{X_{qe}} + \left(\frac{1}{X''_{qe}} - \frac{1}{X_{qe}}\right)\varepsilon^{-t/\tau''_{qe}}\right]$$
$$+ V_m\left(\frac{1}{X''_{qe}} - \frac{1}{X_{qe}}\right)\sum_{n=1}^{\infty}\varepsilon^{-(t-n\Delta t)/\tau''_{qe}}\sin\delta(n\Delta t) \quad . \quad . \quad (23)$$

$(n\Delta t)$ is the value of δ after n intervals.

he application of eqns. (22) and (23) becomes very tedious if calculation has to be carried out over a large number of s, because the calculation of the nth step requires the summa- of n quantities in each of the three summation terms.

(4.4) Approximate Calculation of the Torque

y using the partial-fraction forms of eqns. (70) and (69), ectively, the currents given by eqns. (19) can each be split up three parts as follows:

$$\left.\begin{aligned} i_{d1} &= i_{do} - \frac{1}{X'_{de}}[V_m(\cos\delta - \cos\delta_0) + X_e i_{do}]1 \\ i_{q1} &= i_{qo} + \frac{1}{X_{qe}}[V_m(\sin\delta - \sin\delta_0) - X_e i_{qo}]1 \end{aligned}\right\} \quad . \quad (24)$$

$$\left.\begin{aligned} i_{d2} &= \left(\frac{1}{X'_{de}} - \frac{1}{X_{de}}\right)\frac{1}{1+\tau'_{de}p}[V_m(\cos\delta - \cos\delta_0) \\ &\qquad + X_e i_{do}]1 \\ i_{q2} &= 0 \end{aligned}\right\} \quad (25)$$

$$\left.\begin{aligned} i_{d3} &= -\left(\frac{1}{X''_{de}} - \frac{1}{X'_{de}}\right)\frac{\tau''_{de}p}{1+\tau''_{de}p} \\ &\qquad [V_m(\cos\delta - \cos\delta_0) + X_e i_{do}]1 \\ i_{q3} &= \left(\frac{1}{X''_{qe}} - \frac{1}{X_{qe}}\right)\frac{\tau''_{qe}p}{1+\tau''_{qe}p} \\ &\qquad [V_m(\sin\delta - \sin\delta_0) - X_e i_{qo}]1 \end{aligned}\right\} \quad (26)$$

orresponding to each pair of currents (i_{d1}, i_{q1}), (i_{d2}, i_{q2}) and $, i_{q3})$, torque components T_{e1}, T_{e2} and T_{e3} can be calculated from eqn. (21). In the following Sections approximate expressions for the three torque components are derived.

(4.4.1) First Torque Component.

The operator p does not appear in eqns. (24) and hence the symbol 1 can be omitted. The following expressions are obtained by using the relations of eqns. (74)–(77):

$$\left.\begin{aligned} i_{d1} &= \frac{\sqrt{2}}{X'_{de}}(V'_{qo} - V\cos\delta) \\ i_{q1} &= \frac{\sqrt{2}}{X_{qe}}V\sin\delta \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad (27)$$

$$T_{e1} = -\frac{VV'_{qo}}{X'_{de}}\sin\delta + \frac{V^2}{2}\left(\frac{1}{X'_{de}} - \frac{1}{X_{qe}}\right)\sin 2\delta \quad . \quad (28)$$

T_{e1} is thus the torque produced on the assumption that the field flux linkages are constant (see Reference 7).

(4.4.2) Second Torque Component.

After the switch closes the field flux linkages do, in fact, change and V'_q, the voltage behind transient reactance, varies in dependence on δ, the relation being that given by eqn. (77) without the suffix o:

$$V'_q = V\cos\delta + X'_d I_d \quad . \quad . \quad . \quad . \quad (29)$$

Let V'_{q2} be the change of V'_q from its original value V'_{qo}:

$$V'_q = V'_{qo} + V'_{q2} \quad . \quad . \quad . \quad . \quad . \quad (30)$$

The torque associated with the change of V'_q is, from eqn. (28),

$$T_{e2} = -\frac{VV'_{q2}}{X'_{de}}\sin\delta \quad . \quad . \quad . \quad . \quad . \quad (31)$$

T_{e2} is also the second component of torque due to i_{d2} and i_{q2} in eqn. (25). Hence, from eqn. (21), since $i_{q2} = 0$,

$$T_{e2} = -\frac{V}{\sqrt{2}}i_{d2}\sin\delta \quad . \quad . \quad . \quad . \quad (32)$$

Comparing eqns. (31) and (32) and using eqn. (25),

$$V'_{q2} = \left(\frac{X_{de} - X'_{de}}{X_{de}}\right)\frac{1}{1+\tau'_{de}p}[V(\cos\delta - \cos\delta_0) + X_e I_{do}] \quad (33)$$

Multiplying by $1 + \tau'_{de}p$ and using eqns. (76) and (77),

$$T'_{de}\frac{dV'_{q2}}{dt} + V'_{q2} = \left(1 - \frac{X'_{de}}{X_{de}}\right)V\cos\delta - V'_{qo} + \frac{X'_{de}}{X_{de}}V_0 \quad (34)$$

Hence, using eqn. (30), since V'_{qo} is constant,

$$\frac{dV'_q}{dt} = \frac{1}{\tau'_{de}}\left[-V'_q + \frac{X'_{de}}{X_{de}}V_0 + \left(1 - \frac{X'_{de}}{X_{de}}\right)V\cos\delta\right] \quad (35)$$

Eqn. (35), which agrees with the expression given by Crary[7] and Kimbark,[12] can be used to calculate V'_q by a step-by-step method, and hence to determine T_{e2}.

(4.4.3) Third Torque Component.

The third component arises because of the presence of the damper winding. The current components are calculated from eqn. (26) by using the approximate standard form of eqn. (81):

$$\left.\begin{aligned} i_{d3} &= \left(\frac{1}{X''_{de}} - \frac{1}{X'_{de}}\right)\left[-X_e i_{do}\varepsilon^{-t/\tau''_{de}} + V_m\tau''_{de}\sin\delta\frac{d\delta}{dt}(1-\varepsilon^{-t/\tau''_{de}})\right] \\ i_{q3} &= \left(\frac{1}{X''_{qe}} - \frac{1}{X_{qe}}\right)\left[-X_e i_{qo}\varepsilon^{-t/\tau''_{qe}} + V_m\tau''_{qe}\cos\delta\frac{d\delta}{dt}(1-\varepsilon^{-t/\tau''_{qe}})\right] \end{aligned}\right\} \quad (36)$$

The torque is obtained by substituting eqns. (36) in eqn. (21) and using eqns. (74) and (75).

$$T_{e3} = -(a\sin^2\delta + b\cos^2\delta)s$$

$$+ V\sin\delta\left(\frac{1}{X''_{de}} - \frac{1}{X'_{de}}\right)(X_e I_{do} + \omega s\tau''_{de}V\sin\delta)\varepsilon^{-t/\tau''_{de}}$$

$$+ V\cos\delta\left(\frac{1}{X''_{qe}} - \frac{1}{X_{qe}}\right)(X_e I_{qo} + \omega s\tau''_{qe}V\cos\delta)\varepsilon^{-t/\tau''_{qe}} \quad (37)$$

where

$$\left.\begin{aligned} a &= \omega V^2\tau''_{de}\left(\frac{1}{X''_{de}} - \frac{1}{X'_{de}}\right) \\ b &= \omega V^2\tau''_{qe}\left(\frac{1}{X''_{qe}} - \frac{1}{X_{qe}}\right) \\ \text{and} \quad \omega s &= \frac{d\delta}{dt} \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad (38)$$

The second and third terms die away rapidly and, if these are neglected, the damping torque is

$$T_{e3} = -(a\sin^2\delta + b\cos^2\delta)s \quad . \quad . \quad . \quad (39)$$

If a and b are nearly equal, eqn. (39) can be further simplified to

$$T_{e3} = -\frac{(a+b)}{2}s \quad . \quad . \quad . \quad . \quad . \quad (40)$$

(4.5) Practical Application of the Torque Formulae

The total electrical torque produced by the machine, following the disturbance, is given approximately by

$$\begin{aligned} T_e &= T_{e1} + T_{e2} + T_{e3} \\ &= -\frac{VV'_{qo}}{X'_{de}}\sin\delta + \frac{V^2}{2}\left(\frac{1}{X'_{de}} - \frac{1}{X_{qe}}\right)\sin 2\delta \\ &\quad - \frac{VV'_{q2}}{X'_{de}}\sin\delta - (a\sin^2\delta + b\cos^2\delta)s \quad . \quad (41) \end{aligned}$$

The division of torque into three components leads to alternative methods of calculation with different degrees of approximation. The more accurate methods require a correspondingly greater amount of computation.

The first torque component is that obtained by the well-known method based on the assumptions of constant flux linkage. In practical work, particularly for network analyser studies on multi-machine systems, the further assumption is usually made that $X'_d = X_q$. The method gives a pessimistic result but is, for many purposes, adequate for determining whether the machine is likely to go out of synchronism on the first swing. It is grossly inaccurate for determining the behaviour after the first swing, since it leaves out of account the effect of the damper winding and the variation of the field flux linkages.

The second torque component allows for the variation of field flux linkage but ignores the effect of the damper winding. The quantity V'_{q2} is a measure of the change in the field flux linkage.

The third torque component is a damping torque which is proportional to the slip and is produced by the action of the damper winding. The value of the damping coefficient depends on the instantaneous load angle, but if the two quantities a and b in eqn. (41) are nearly equal, as they often are, the damping coefficient is approximately constant, as in eqn. (40).

(4.6) Comparison of Calculations and Tests

(4.6.1) Stable Condition.

For the first part of the investigation the operation after the disturbance was stable. The reactance was such that the machine rotor, after a period of swinging, settled down to a new condition of synchronous operation. In the original steady condition the per-unit values were

$V = 1\cdot01$	$v_{do} = -0\cdot69$
$I = 1\cdot60$	$v_{qo} = 1\cdot24$
$\cos\phi = 0\cdot97$ lag	$i_{do} = 1\cdot54$
$V_o = 1\cdot87$	$i_{q0} = -1\cdot63$
$I_f = 2\cdot18$	$\delta_0 = -29\cdot2°$

The external reactance and the inertia constant were $X_e = 0\cdot284$, $H = 4\cdot25$ sec.

The time-constant regulator was not used for this test, with the result that the transient time-constants are a good deal shorter than those of a typical large machine. The parameters used for the calculations are those given in Section 2, except that saturated values of synchronous reactance were determined from measurements made under the original steady condition:

$$X_{d(sat)} = 0\cdot88 \qquad X_{q(sat)} = 0\cdot44$$

The measured curves of load angle and torque are shown dotted in Figs. 8 and 9. The dotted curve of Fig 9 was

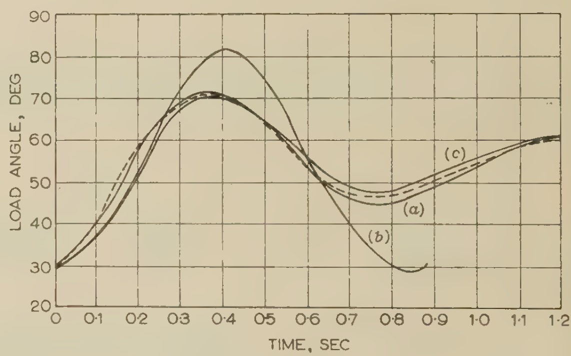
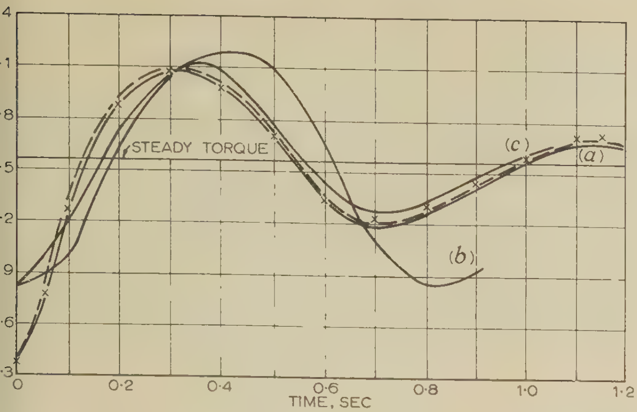


Fig. 8.—Variation of load angle after inserting a reactance (stable condition).

---- Test.
—— Calculated.
(a) Accurate method.
(b) Assuming constant flux linkage and no damping.
(c) Allowing for variable flux linkage and damping.

measured by the torque coupling, while the crosses indicate the torque deduced from an oscillogram of power input. It is evident that the torque is determined sufficiently accurately by a power measurement. The stability can, in fact, be fully assessed from the load-angle curve and no torque measurements were made on subsequent swing-curve tests.

The calculated curves, using three different methods, are shown by full lines in Figs. 8 and 9. Curves (a) were calculated by the accurate method described in Section 4.3. The good agreement with the measured curves confirms that the assumptions made in deriving eqns. (19) are acceptable and that the values of the parameters are satisfactory.



;. 9.—Torque curves corresponding to the angle curves of Fig. 8.

Curves (*b*) were calculated from the first torque component, of eqn. (28). The method is the one normally used for nsient stability analysis, except that it allows for transient ency. It is based on the assumption of constant field flux tage and is clearly pessimistic, even during the first swing.

Curves (*c*) in Figs. 8 and 9 were calculated from the full expres- n for torque in eqn. (41). The agreement with the accurate thod and with the measurements is good, although there is ne discrepancy in the torque curve during the first 0·1 sec, ause of the omission of the second and third terms of eqn. (37). s method was therefore adopted as the approved one for er work because the computation required is very much less n for curves (*a*). It confirms that the approximations made deriving eqn. (41) are acceptable.

.2) Unstable Condition.

For the second part of the investigation the field excitation s reduced so that the machine pulled out of step after the turbance. The time-constant regulator was introduced, reby increasing the effective transient time-constant, τ_d', to 92 sec. Otherwise the machine parameters and the external ctance were as before, except that new saturated values, $_{sat)} = 0{\cdot}99$ and $X_{q(sat)} = 0{\cdot}45$, were used.

The damping coefficients were widely different in this example, ng $a = 6{\cdot}7$, $b = 34{\cdot}5$.

The quantities in the original steady condition (per-unit ues) were

$V = 1{\cdot}01$	$v_{do} = -1{\cdot}04$
$I = 1{\cdot}80$	$v_{qo} = 0{\cdot}94$
$\cos\phi = 0{\cdot}86$ lead	$i_{do} = 0{\cdot}82$
$V_o = 1{\cdot}27$	$i_{qo} = -2{\cdot}50$
$I_f = 1{\cdot}40$	$\delta_o = -48{\cdot}8°$

The measured curve of load angle is shown dotted in Fig. 10. e torque curve was not recorded and no calculations were de by the method of Section 4.3. On the other hand, several proximate curves, based on different combinations of the que components, were calculated using a digital computer.

Curve (*a*) of Fig. 10 is calculated from eqn. (28) and assumes nstant flux linkage and no damping.

Curve (*b*), which is calculated from eqn. (41), allows for varia- n of field flux linkage and for damping.

Curve (*c*), which is calculated from $T_{e1} + T_{e3}$, allows for mping but assumes constant flux linkage.

Curve (*d*), which is calculated from $T_{e1} + T_{e2}$, allows for iation of flux linkage but not for damping.

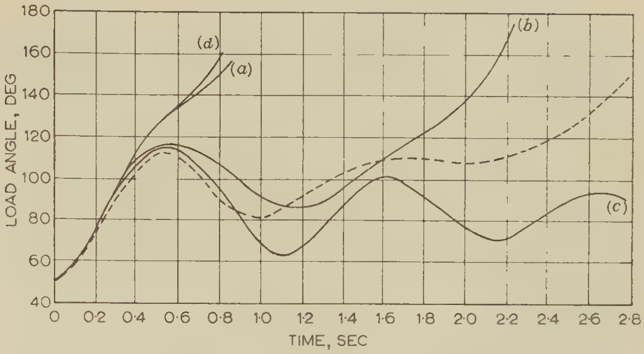


Fig. 10.—Variation of load angle after inserting a reactance (unstable condition).

---- Test.
—— Calculated.

(*a*) Assuming constant flux linkage and no damping.
(*b*) Allowing for variable flux linkage and damping.
(*c*) Allowing for damping but assuming constant flux linkage.
(*d*) Allowing for variable flux linkage but assuming no damping.

The results show that for a true assessment of stability both damping and the flux linkage variation must be included. It is sometimes stated that the two effects approximately cancel, but the results shown demonstrate clearly that this is not so, although it is true that they act in opposite directions. Curve (*d*) is even more pessimistic than (*a*), while (*c*), which allows for damping but not for flux variation, indicates incorrectly that the condition tested is stable.

(5) ASYNCHRONOUS OPERATION

(5.1) General

An alternator which loses synchronism but remains connected to the supply system may settle down after a time to a steady condition of operation as an asynchronous generator. For a given power output, the currents are increased compared with the values during normal synchronous operation and the currents in the supply leads pulsate. The speed also pulsates about a mean value. Thus the heating of the machine is increased and the undesirable pulsations may disturb the supply system.

It has been generally accepted in the past that an alternator which loses synchronism must be disconnected forthwith. Recent experience, supported by full-scale tests, has, however, indicated that under certain conditions and for a limited period it is permissible to leave the machine connected until some action can be taken to cause it to resynchronize. It therefore becomes important to understand what happens when an alter- nator runs asynchronously and what are the criteria for resynchronization.

If the field excitation is removed when the machine loses synchronism, the current and torque pulsations are much less severe. The alternator is then an induction generator with unsymmetrical secondary circuits. The theory in the following Sections starts by analysing this condition, during which the field circuit may be closed or open, or closed through a resis- tance. The next step is to allow for the effect of a field voltage. The theory then studies the conditions for resynchronization.

The theoretical analysis given below is an approximate one. During the asynchronous operation the speed of the machine pulsates and an exact analysis would require the solution of non- linear differential equations. The first part of the analysis is therefore based on the assumption that the speed is constant, for which condition the equations are linear. In the second part of the analysis the torque pulsations, calculated from formulae derived in the first part, are used to determine the pulsations of speed.

(5.2) Theoretical Analysis Based on Constant Slip

With a constant slip, s, the load angle increases uniformly with time, i.e. $\delta = s\omega t$. Eqns. (72), neglecting r_a, then become

$$\left.\begin{aligned} V_m \sin s\omega t &= p\psi_d + (1-s)\omega\psi_q \\ V_m \cos s\omega t &= -(1-s)\omega\psi_d + p\psi_q \end{aligned}\right\} \quad . \quad . \quad (42)$$

Eqns. (42) are used in conjunction with eqns. (65). Since the equations are linear, the solution may be obtained by superimposing two separate parts, for which additional suffixes are used: suffix 1, solution with applied terminal voltage but no field voltage; suffix 2, solution with applied field voltage but no terminal voltage.

The field resistance, r_f, must include any external resistance in the circuit.

(5.2.1) Calculation of Torque with no Field Voltage.

During steady operation with $v_f = 0$, the axis currents and the flux linkages obtained by the solution of eqns. (42) and (65) are sinusoidal quantities at slip frequency. The equations can be converted into vector equations by substituting $p = js\omega$ and replacing the variables by the corresponding vectors, indicated by symbols in bold type.

$$\left.\begin{aligned} -j\boldsymbol{V} &= js\omega\boldsymbol{\psi}_{d1} + (1-s)\omega\boldsymbol{\psi}_{q1} \\ \boldsymbol{V} &= -(1-s)\omega\boldsymbol{\psi}_{d1} + js\omega\boldsymbol{\psi}_{q1} \end{aligned}\right\} \quad . \quad . \quad . \quad (43)$$

$$\left.\begin{aligned} \omega\boldsymbol{\psi}_{d1} &= X_d(js\omega)\boldsymbol{I}_{d1} \\ \omega\boldsymbol{\psi}_{q1} &= X_q(js\omega)\boldsymbol{I}_{q1} \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (44)$$

$$\left.\begin{aligned} \omega\boldsymbol{\psi}_{d1} &= -\boldsymbol{V} \\ \omega\boldsymbol{\psi}_{q1} &= -j\boldsymbol{V} \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (45)$$

$$\left.\begin{aligned} \boldsymbol{I}_{d1} &= \frac{-\boldsymbol{V}}{X_d(js\omega)} = -\boldsymbol{V}(Y_a + jY_b) \\ \boldsymbol{I}_{q1} &= \frac{-\boldsymbol{V}}{X_q(js\omega)} = \boldsymbol{V}(Y_d - jY_c) \end{aligned}\right\} \quad . \quad . \quad . \quad (46)$$

The instantaneous values of the flux linkages and currents are therefore given by

$$\left.\begin{aligned} \omega\psi_{d1} &= -V_m \cos s\omega t \\ \omega\psi_{q1} &= V_m \sin s\omega t \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (47)$$

$$\left.\begin{aligned} i_{d1} &= -V_m(Y_a \cos s\omega t - Y_b \sin s\omega t) \\ i_{q1} &= V_m(Y_d \cos s\omega t + Y_c \sin s\omega t) \end{aligned}\right\} \quad . \quad . \quad (48)$$

Substituting eqns. (47) and (48) in eqn. (64), the corresponding torque component is obtained:

$$T_{e1} = \frac{-V^2}{2}[(Y_b + Y_d) + (Y_c - Y_a)\sin 2s\omega t + (Y_d - Y_b)\cos 2s\omega t] \quad (49)$$

The mean torque is

$$T_{e(mean)} = \frac{-V^2}{2}(Y_b + Y_d) \quad . \quad . \quad . \quad (50)$$

(5.2.2) Calculation of Torque with a Field Voltage.

The torque component T_{e2} resulting from the application of a field voltage is calculated by putting $V_m = 0$ in eqns. (42). The machine is now an alternator with zero terminal voltage, i.e. a short-circuited armature, running at constant speed. The axis currents and flux linkages are constant quantities and the solution is obtained by putting $p = 0$:

$$\psi_{d2} = 0 \quad \psi_{q2} = 0 \quad . \quad . \quad . \quad . \quad . \quad (51)$$

$$\left.\begin{aligned} i_{d2} &= \frac{-X_{md}}{r_f X_d} v_f \\ i_{q2} &= 0 \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (52)$$

The components of eqns. (51) and (52) by themselves would produce no torque, but there is a torque due to the interaction of i_{d2} and ψ_{q1}.

The total torque of a machine, running asynchronously with supply voltage V and field voltage v_f, is therefore

$$T_e = -\frac{V^2}{2}[(Y_b + Y_d) + (Y_c - Y_a)\sin 2s\omega t + (Y_d - Y_b)\cos 2s\omega t] - \frac{VV_0}{X_d}\sin s\omega t \quad (53)$$

where

$$V_0 = -\frac{1}{\sqrt{2}}\frac{X_{md}}{r_f}v_f \quad . \quad . \quad . \quad . \quad (54)$$

V_0 is the open-circuit voltage induced by the excitation at synchronous speed.

(5.3) Calculation of Slip Pulsations

The behaviour of the machine when running asynchronously under practical operating conditions differs from that considered in Section 5.2 because the torque pulsations cause the slip to oscillate about a mean value. The method given below for calculating the slip variations is based on the assumptions that the prime-mover torque has the constant value given by eqn. (50) and that the electrical torque is still given by eqn. (53) with $s\omega t$ replaced by δ.

The equation of motion is then

$$\frac{2H}{\omega}\frac{d^2\delta}{dt^2} = -\frac{VV_0}{X_d}\sin\delta - \frac{V^2}{2}(Y_c - Y_a)\sin 2\delta - \frac{V^2}{2}(Y_d - Y_b)\cos 2\delta \quad (55)$$

Multiplying by $\frac{d\delta}{dt}$ and integrating, using $s\omega = \frac{d\delta}{dt}$,

$$\omega H s^2 = \frac{VV_0}{X_d}\cos\delta + \frac{V^2}{4}(Y_c - Y_a)\cos 2\delta - \frac{V^2}{4}(Y_d - Y_b)\sin 2\delta + X \quad (56)$$

X is a constant of integration, which is equal to the mean value, taken with respect to δ, of the function on the right-hand side, and is given by $X = \omega H s_0^2$. Consequently,

$$s^2 = s_0^2 + \frac{1}{\omega H}\left[\frac{VV_0}{X_d}\cos\delta + \frac{V^2}{4}(Y_c - Y_a)\cos 2\delta - \frac{V^2}{4}(Y_d - Y_b)\sin 2\delta\right] \quad (57)$$

(5.4) Comparison of Calculations and Tests

(5.4.1) The Operational Impedances.

Tests during asynchronous operation were carried out on the micro-alternator described in Section 2. The field resistance varied from 0·0007 per unit, with the time-constant regulator in use, to large values of r_f including external resistance.

The calculations of torque and slip from eqns. (53) and (57) depend on a correct estimation of Y_a, Y_b, Y_c and Y_d, which are derived from the operational impedances $X_d(js\omega)$ and $X_q(js\omega)$ at given values of slip. The functions are given by eqns. (66) in terms of two synchronous reactances and six time-constants, but it must be remembered that these expressions depend on

ny assumptions. For the model machine, which has a inated rotor, the formulae are reasonably exact when r_f is ill, but are less so for large values of r_f, because of the umptions made in deriving $X_d(p)$ in eqn. (66) from eqns. (62). calculating the curves of Figs. 11 and 12 for large values of r_f, re correct formulae based on the fundamental equations e used.

The method would give quite accurate results when applied to ypical waterwheel generator but it is much less exact for a m turbo-generator with a solid rotor, because the repre- tation of the damper system by a single winding on each s is inaccurate. The concept of the operational impedance ctions is still valid, but there is a need for improved methods calculating and measuring their values.

.2) Torque/Slip Curves.

Fig. 11 shows a set of curves relating mean torque and mean during operation as an asynchronous generator when the chine is connected directly to the fixed supply. Fig. 12 shows ilar curves for the same machine with an external reactance = 0·19 per unit. In each case there is no excitation and ves are shown for different values of r_f. The measured curves are shown by dotted lines and the calculated curves by full lines.

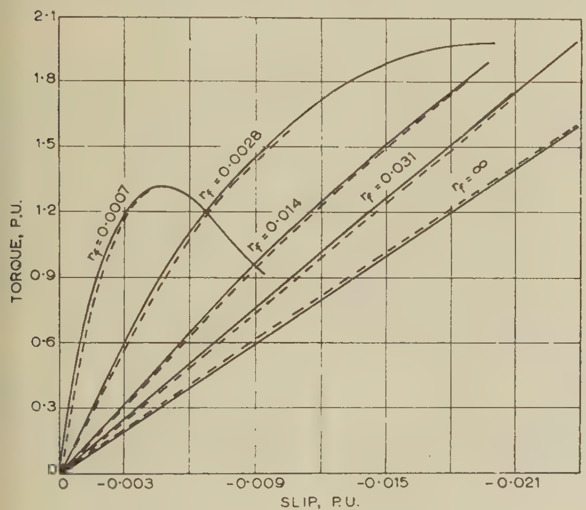


Fig. 11.—Torque/slip curves ($X_e = 0$).
---- Test.
—— Calculated.

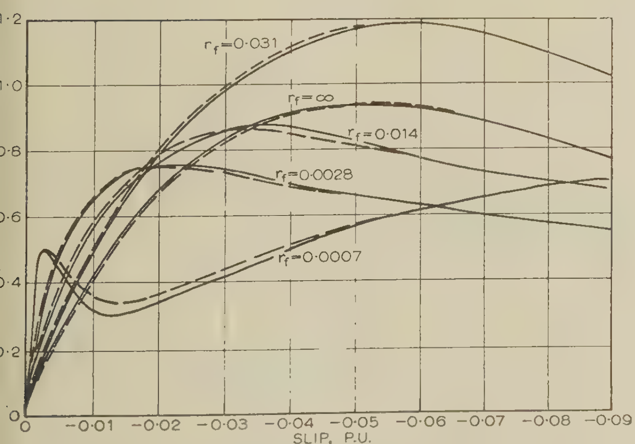


Fig. 12.—Torque/slip curves ($X_e = 0{\cdot}19$ p.u.).
---- Test.
—— Calculated.

The slip was measured by counting the oscillations of a volt- meter connected to an auxiliary winding on the alternator rotor. The torque at higher slips was determined from wattmeter readings, but this method was inaccurate at low slips because of the pulsations. At low slips, the mean torque was deduced from torque oscillograms obtained with the torque meter.

(5.4.3) Torque Oscillations.

Fig. 13 shows the variation of torque with load angle for three values of mean slip when the machine is operating asynchro- nously with no field. The period of the oscillation, which is half a slip cycle, is marked as π radians. The dotted lines show measured values, obtained with the torque meter and the load- angle meter. The full lines are calculated from eqn. (49). The assumption that the slip is constant, on which eqn. (49) depends, is more nearly true at higher slips and there is good agreement between calculation and test in Fig. 13(*c*). At low slips the measured curve agrees less well with the calculated sine wave, although the peak value is about the same.

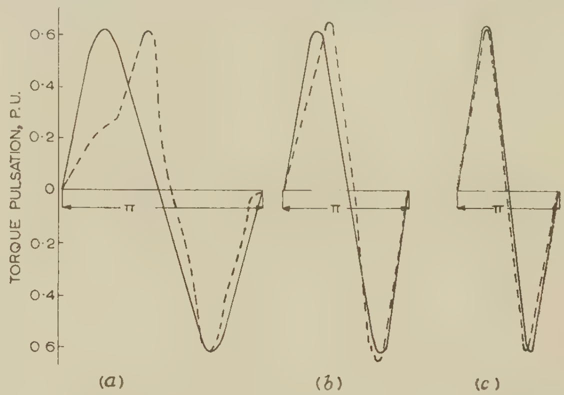


Fig. 13.—Variation of torque with load angle (without field).
---- Test.
—— Calculated.
(*a*) $s_o = -0{\cdot}007$.
(*b*) $s_o = -0{\cdot}011$.
(*c*) $s_o = -0{\cdot}015$.

Fig. 14 shows the variation of torque when the field is excited

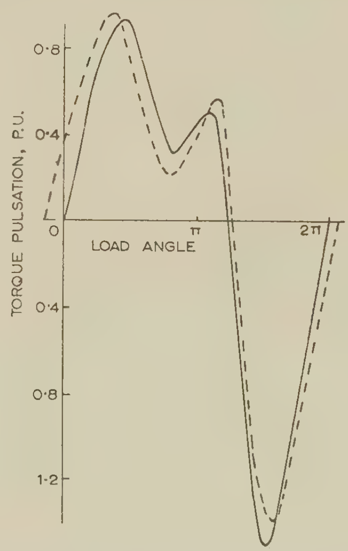


Fig. 14.—Variation of torque with load angle (with field).
---- Test.
—— Calculated.

and the mean slip has a low value. Both the calculated and measured curves show the presence of the components at slip frequency and twice slip frequency in eqn. (53).

(6) RESYNCHRONIZATION

(6.1) The Slip/Angle Curve

When a synchronous machine is running out of synchronism the operation can be studied by plotting a curve showing the variation of slip with load angle. Fig. 15 (dotted line) shows

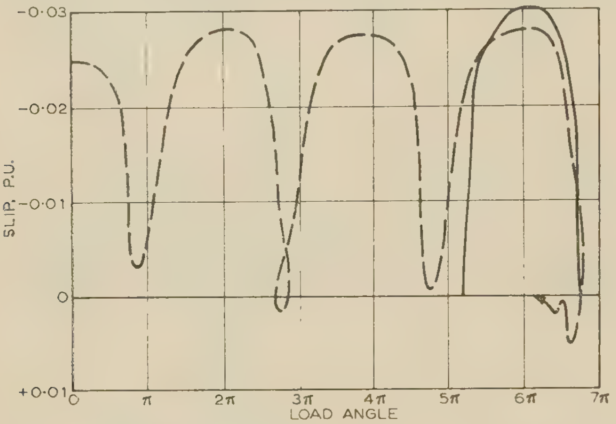


Fig. 15.—Variation of slip with load angle (with field).
---- Test.
—— Calculated.

such a curve, obtained by test, for a condition on the borderline between asynchronous and synchronous operation. During three slip cycles the machine approaches zero slip without synchronizing, but pulls in at the fourth attempt. The full line in Fig. 15 is the corresponding curve calculated from eqn. (57). For a given condition of supply and excitation it is suggested that an approximate criterion for resynchronization can be obtained by calculating the slip/angle curve from eqn. (57) and determining whether the minimum point reaches zero.

It is assumed that no sudden change in the conditions takes place, i.e. that the load torque, the field voltage and the external circuit remain fixed or change slowly. A sudden increase of field voltage at certain instants, for example, would make the machine more likely to synchronize. The criterion suggested above covers the worst condition. To apply the criterion, the mean slip for any specified load is first taken from a curve based on eqn. (50) and the minimum slip is calculated from eqn. (57). If the minimum value of s^2 is zero or negative the machine will synchronize.

It may be noted that an error occurs because s_0, which should strictly be the mean value with respect to δ, is not necessarily the same as the value taken. Moreover, the slip may fall to zero without causing the machine to synchronize, as shown by the second swing of Fig. 15. The method must therefore be regarded as empirical, since the theoretical basis is not rigorous.

The dotted curves (*a*) and (*b*) of Fig. 16 show the maximum load, determined by tests, at which the machine synchronizes with two values of the inertia constant H. Curve (*c*) shows the stability limit at which the machine would fall out of step if already in synchronism. The full-line curves are calculated by the method outlined above, using eqn. (57).

(6.2) An Approximate Equation with Constant Coefficients

The equations of a synchronous machine operating out of synchronism are non-linear, of the second order or higher.

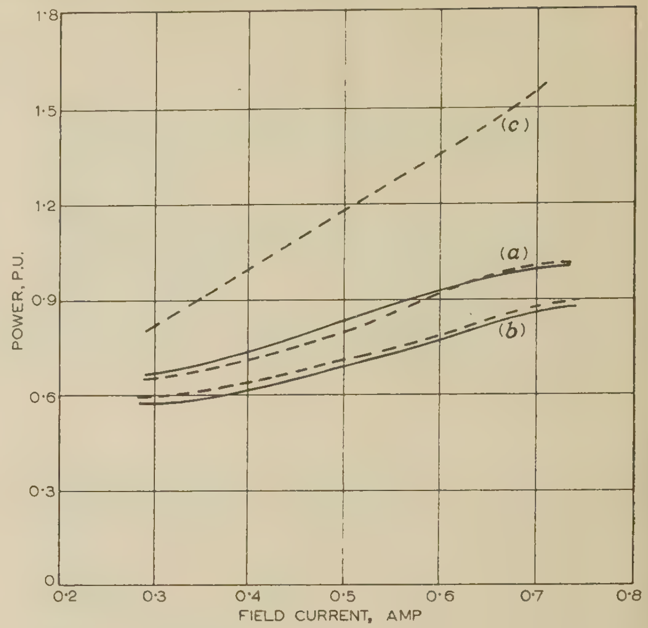


Fig. 16.—Limiting load for resynchronization at different field currents.
---- Test.
—— Calculated.
(*a*) $H = 5\cdot1$ sec.
(*b*) $H = 8\cdot0$ sec.
(*c*) Shows the load at which the machine pulls out if already in synchronism.

Such equations have been studied using the methods of non-linear mechanics by considering curves relating a displacement variable to a speed variable. In the language of non-linear mechanics, the curves are called 'trajectories in the phase plane'. In the synchronous machine the displacement is the angle δ and the speed is the slip, s. Thus the slip/angle curve is a trajectory of this kind.[13]

Eqn. (57) contains the coefficients Y_a, Y_b, Y_c and Y_d which are themselves functions of s. They can, however, be evaluated approximately by putting $p = js\omega$ in the partial fractions of eqns. (68) and (69) and rationalizing the separate terms.

$$\left.\begin{aligned} Y_a + jY_b &= \frac{1}{X_d(js\omega)} \\ &= \frac{1}{X_d} + \left(\frac{1}{X'_d} - \frac{1}{X_d}\right)\frac{js\omega\tau'_d + s^2\omega^2\tau'^2_d}{1 + s^2\omega^2\tau'^2_d} \\ &\quad + \left(\frac{1}{X''_d} - \frac{1}{X'_d}\right)\frac{js\omega\tau''_d + s^2\omega^2\tau''^2_d}{1 + s^2\omega^2\tau''^2_d} \\ Y_c + jY_d &= \frac{1}{X_q} + \left(\frac{1}{X''_q} - \frac{1}{X_q}\right)\frac{js\omega\tau''_q + s^2\omega^2\tau''^2_q}{1 + s^2\omega^2\tau''^2_q} \end{aligned}\right\} \quad (58)$$

For the range of slips under consideration $s^2\omega^2\tau'^2_d$ is much larger than unity, and $s^2\omega^2\tau''^2_d$ and $s^2\omega^2\tau''^2_q$ are much less than unity. Hence approximately,

$$\left.\begin{aligned} Y_a &= \frac{1}{X'_d} \\ Y_b &= \left(\frac{1}{X''_d} - \frac{1}{X'_d}\right)s\omega\tau''_d \\ Y_c &= \frac{1}{X_q} \\ Y_d &= \left(\frac{1}{X''_q} - \frac{1}{X_q}\right)s\omega\tau''_q \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad (59)$$

n. (53) becomes

$$= -\frac{VV_0}{X_d}\sin\delta + \frac{V^2}{2}\left(\frac{1}{X_d'} - \frac{1}{X_q}\right)\sin 2\delta - \frac{(a+b)}{2}s + \frac{(a-b)}{2}s\cos 2\delta \quad . \quad (60)$$

ere a and b are the damping coefficients defined in eqn. (38). Equations of this type have been studied by the methods of n-linear mechanics.[14]

(7) CONCLUSION

The mathematical analysis developed in the paper provides a oretical basis for studying the operation of a synchronous chine away from synchronism and the measurements taken h the micro-machine equipment for several important ctical conditions confirm that the calculations based on them reasonably accurate. Further work is needed to examine in re detail the factors which control resynchronization and to end the method in order to deal with multi-machine systems d to allow for the effects of voltage regulators and governors.

(8) ACKNOWLEDGMENTS

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(10) APPENDICES

(10.1) The Equations of the Synchronous Machine

(10.1.1) Fundamental Equations.

The fundamental differential equations relating the instantaneous values of the voltages, currents, flux linkages, torque and speed of a synchronous machine are as follows:

$$\left.\begin{aligned} v_d &= p\psi_d + u\psi_q + r_a i_d \\ v_q &= -u\psi_q + p\psi_d + r_a i_q \end{aligned}\right\} \quad . \quad . \quad . \quad (61)$$

$$\left.\begin{aligned} \psi_d &= L_{md}i_f + L_{md}i_{kd} + (L_{md} + L_a)i_d \\ v_f &= [r_f + (L_{md} + L_f)p]i_f + L_{md}pi_{kd} + L_{md}pi_d \\ 0 &= L_{md}pi_f + [r_{kd} + (L_{md} + L_{kd})p]i_{kd} + L_{md}pi_d \end{aligned}\right\} \quad (62)$$

$$\left.\begin{aligned} \psi_q &= L_{mq}i_{kq} + (L_{mq} + L_a)i_q \\ 0 &= [r_{kq} + (L_{mq} + L_{kq})p]i_{kq} + L_{mq}pi_q \end{aligned}\right\} \quad . \quad . \quad . \quad (63)$$

$$T_e = \frac{\omega}{2}(\psi_d i_q - \psi_q i_d) \quad . \quad . \quad . \quad (64)$$

The following equations are obtained by eliminating i_f and i_{kd} from eqns. (62) and i_{kq} from eqns. (63):

$$\left.\begin{aligned} \omega\psi_d &= X_d(p)i_d + G(p)v_f \\ \omega\psi_q &= X_q(p)i_q \end{aligned}\right\} \quad . \quad . \quad . \quad (65)$$

where the operational impedances $X_d(p)$ and $X_q(p)$ and the transfer function $G(p)$ are given by

$$\left.\begin{aligned} X_d(p) &= \frac{(1+\tau_d'p)(1+\tau_d''p)}{(1+\tau_{do}'p)(1+\tau_{do}''p)}X_d \\ X_q(p) &= \frac{(1+\tau_q''p)}{(1+\tau_{qo}''p)}X_q \end{aligned}\right\} \quad . \quad . \quad (66)$$

$$G(p) = \frac{X_{md}}{r_f}\,\frac{(1+\tau_{kd}p)}{(1+\tau_{do}'p)(1+\tau_{do}''p)} \quad . \quad . \quad (67)$$

(10.1.2) Partial-Fraction Forms.

The reciprocals of the operational impedances may be expressed as sums of partial fractions. If τ_d'' and τ_{do}'' are much smaller than τ_d' and τ_{do}', the expressions are approximately as follows:

$$\frac{1}{X_d(p)} = \frac{1}{X_d} + \left(\frac{1}{X_d'} - \frac{1}{X_d}\right)\frac{\tau_d'p}{1+\tau_d'p} + \left(\frac{1}{X_d''} - \frac{1}{X_d'}\right)\frac{\tau_d''p}{1+\tau_d''p} \quad . \quad . \quad . \quad (68)$$

$$\frac{1}{X_q(p)} = \frac{1}{X_q} + \left(\frac{1}{X_q''} - \frac{1}{X_q}\right)\frac{\tau_q''p}{1+\tau_q''p} \quad . \quad . \quad . \quad (69)$$

An alternative form of $1/X_d(p)$ is

$$\frac{1}{X_d(p)} = \frac{1}{X_d'} - \left(\frac{1}{X_d'} - \frac{1}{X_d}\right)\frac{1}{1+\tau_d'p} + \left(\frac{1}{X_d''} - \frac{1}{X_d'}\right)\frac{\tau_d''p}{1+\tau_d''p} \quad (70)$$

(10.1.3) Simplified Equations for a Machine Connected to a Fixed Supply.

For a machine connected to a fixed supply, of which the voltage of phase A is $e_a = V_m \sin \omega t$, eqns. (61) may be

rearranged so as to include the load angle δ as a variable, instead of the speed u, since

$$u = \frac{d}{dt}(\omega t - \delta) = \omega - p\delta \quad . \quad . \quad . \quad . \quad (71)$$

The rearranged equations are

$$\left.\begin{aligned} V_m \sin\delta &= p\psi_d + \omega\psi_q + r_a i_q - \psi_d p\delta \\ V_m \cos\delta &= -\omega\psi_d + p\psi_q + r_a i_q + \psi_d p\delta \end{aligned}\right\} \quad . \quad (72)$$

For the slow transient changes considered in the paper the terms which depend on the rate of change of ψ_d, ψ_q or δ can be neglected, as well as the resistance drops. Eqns. (72) simplify to

$$\left.\begin{aligned} V_m \sin\delta &= \omega\psi_q \\ -V_m \cos\delta &= \omega\psi_d \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad (73)$$

The two voltages in eqns. (73) correspond to the components of the terminal voltage in the steady-state vector diagram of Fig. 17. Thus a vector diagram can be used to represent the conditions at any instant during a slow transient, but the diagram changes from one instant to another.

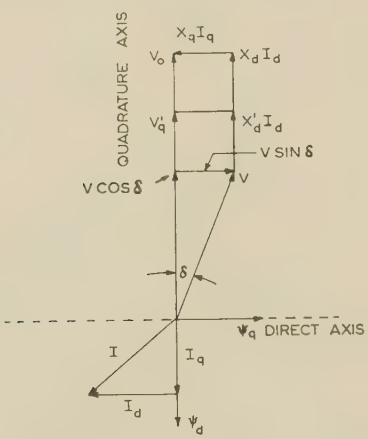

Fig. 17.—Vector diagram for the steady state or for slow transient conditions.

(10.1.4) **Steady Synchronous Operation.**

During steady operation the axis voltages and currents are constant quantities and are related to the components of the vectors in the vector diagram of Fig. 17. The symbols in eqns. (74)–(77) have the suffix o because they are used in the text for the original steady values existing before the disturbance. The resistance r_a is neglected.

The axis currents are related to the components of the current vector I_0 as follows:

$$i_{do} = (\sqrt{2})I_{do} \quad i_{qo} = -(\sqrt{2})I_{qo} \quad . \quad . \quad . \quad (74)$$

V, the r.m.s. value of the terminal voltage, is

$$V = V_m/\sqrt{2} \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (75)$$

In the vector diagram,

$$V\cos\delta_o = V_o - X_d I_{do} \quad V\sin\delta_o = -X_q I_{qo} \quad . \quad (76)$$

V_o is the voltage behind the synchronous reactance. The diagram also shows V'_{qo}, the voltage behind the transient reactance:

$$V'_{qo} = V\cos\delta_o + X'_d I_{do} \quad . \quad . \quad . \quad . \quad (77)$$

(10.2) **Heaviside Standard Forms**

In the following expressions α and β are assumed to be small compared with ω:

$$\left.\begin{aligned} \frac{\omega^2}{p^2 + 2\alpha p + \omega^2}1 &= 1 - \varepsilon^{-\alpha t}\cos\omega t - \frac{\alpha}{\omega}\varepsilon^{-\alpha t}\sin\omega t \\ \frac{\omega p}{p^2 + 2\alpha p + \omega^2}1 &= \varepsilon^{-\alpha t}\sin\omega t \\ \frac{\omega^2}{p^2 + 2\alpha p + \omega^2}\,\frac{p}{p+\beta}1 &= \varepsilon^{-\beta t} - \varepsilon^{-\alpha t}\cos\omega t + \left(\frac{\beta - \alpha}{\omega}\right)\varepsilon^{-\alpha t}\sin\omega t \\ \frac{\omega p}{p^2 + 2\alpha p + \omega^2}\,\frac{p}{p+\beta}1 &= -\frac{\beta}{\omega}\varepsilon^{-\beta t} + \varepsilon^{-\alpha t}\sin\omega t + \frac{\beta}{\omega}\varepsilon^{-\alpha t}\cos\omega t \end{aligned}\right\} \quad (78)$$

The following equations, in which $f(t)$ is any function of time are based on Duhamel's Theorem:

$$\frac{p}{p+\beta}f(t)1 = \varepsilon^{-\beta t}f(0) + \sum_{n=1}^{n}\left\{f(n\Delta t) - f[(n-1)\Delta t]\right\}\varepsilon^{\beta(t - n\Delta t)} \quad (79)$$

In eqn. (79), Δt is a small interval of time and n is the number of intervals. $f(n\Delta t)$ is the value of the function after n intervals.

The integral form of eqn. (79) is

$$\frac{p}{p+\beta}f(t)1 = \varepsilon^{-\beta t}f(0) + \int_{\tau=0}^{\tau=t}\varepsilon^{-\beta(t-\tau)}f'(\tau)d\tau \quad . \quad (80)$$

Now if $1/\beta$ is a short time-constant, and $f(t)$ is a slowly changing function, the integral in eqn. (80) may be evaluated approximately by giving $f'(\tau)$ its value at $\tau = t$ and bringing it outside the integral:

$$\frac{p}{p+\beta}f(t)1 = \varepsilon^{-\beta t}f(0) + \frac{1}{\beta}(1 - \varepsilon^{-\beta t})f'(t) \quad . \quad (81)$$

(10.3) **Definitions of the Symbols in the Expressions for the Short-Circuit Current**

$$\left.\begin{aligned} i_{dt} &= v_{qo}\left[\frac{1}{X_d} + \left(\frac{1}{X'_d} - \frac{1}{X_d}\right)\varepsilon^{-t/\tau'_d} + \left(\frac{1}{X''_d} - \frac{1}{X'_d}\right)\varepsilon^{-t/\tau''_d}\right] \\ i_{qt} &= v_{do}\left[\frac{1}{X_q} + \left(\frac{1}{X''_q} - \frac{1}{X_q}\right)\varepsilon^{-t/\tau''_q}\right] \\ R_{d1} &= \left(\frac{1}{X'_d} - \frac{1}{X_d}\right)\frac{X'^2_d}{\omega\tau'_d} \\ R_{d2} &= \left(\frac{1}{X''_d} - \frac{1}{X'_d}\right)\frac{X''^2_d}{\omega\tau''_d} \\ R_q &= \left(\frac{1}{X''_q} - \frac{1}{X_q}\right)\frac{X''^2_q}{\omega\tau''_q} \end{aligned}\right\} \quad (82)$$

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THE MEASUREMENT BASIS OF ELECTRICITY SUPPLY METERING

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SUMMARY

The paper has a threefold object. First, to establish the precise inificance of 3-phase power, reactive volt-amperes and total volt- peres, secondly to examine the suitability of these quantities as a is for a tariff system and thirdly to analyse the possible metering cuits to determine what they actually measure and what are their ors.

The accepted definitions of power, reactive volt-amperes and total t-amperes are established for a single-phase circuit, and the relation ween these and the physical conditions of energy flow is examined. e extension of these concepts to 3-phase systems reveals the some- at arbitrary nature of the quantities which form the basis of many tering systems.

Consideration is then given to what a metering system should empt to measure and whether the integrated values of watt-hours, ctive volt-ampere-hours and total volt-ampere-hours, together with ne indication of maximum demand, give adequate information for assessment of tariff charges.

The analysis of 3-phase metering circuits is made in terms of sym- trical component theory. The possible circuits are tabulated and total measured quantity is specified as a function of the power d reactive volt-amperes of the positive-, negative- and zero-sequence mponents. By comparing these data with the symmetrical com- nents actually present under any particular conditions, the suitability the methods of measurement and their errors are readily derived.

LIST OF SYMBOLS

i, v, p = Instantaneous values of current, voltage and power.
I, V = R.M.S. values of current and voltage.
ω = Angular frequency.
ϕ = Phase angle by which I lags V.
P = Average power.
Q = Reactive volt-amperes.
$\mathbf{I}, \mathbf{V}$ = Phasor (vector) current and voltage.
$\mathbf{I}^*$ = Complex conjugate of $\mathbf{I}$.
I_D, I_F, I_N = D.C., fundamental and Nth harmonic values of I.
V_D, V_F, V_N = D.C., fundamental and Nth harmonic values of V.
P_D, P_F, P_N = D.C., fundamental and Nth harmonic values of P.
Q_D, Q_F, Q_N = D.C., fundamental and Nth harmonic values of Q.
I_1, I_2, I_3 = Line currents (3-phase system).
V_1, V_2, V_3 = Phase voltages (star).
I_{12}, I_{23}, I_{31} = Phase currents (delta).
V_{12}, V_{23}, V_{31} = Line voltages.
I_0 = Neutral current.
V_0, V_s = Neutral or star point potential.
P_1, P_2, P_3 = Phase powers.
Q_1, Q_2, Q_3 = Phase reactive volt-amperes.
I_p, I_n, I_z = Positive-, negative- and zero-sequence components of current in line 1.
V_p, V_n, V_z = Positive-, negative- and zero-sequence components of voltage in phase 1.
${}_pP_p, {}_pQ_p$ = Power and reactive volt-amperes due to positive-sequence components of current and voltage.
${}_nP_n, {}_nQ_n$ = Power and reactive volt-amperes due to negative-sequence components of current and voltage.
${}_zP_z, {}_zQ_z$ = Power and reactive volt-amperes due to zero-sequence components of current and voltage.
${}_nP_p, {}_nQ_p$, etc. = Three times the power and reactive volt-amperes due to V_n and I_p, etc., in one phase.
a = Operator $\angle 120°$.

Convention.

$V_{12} = V_1 - V_2$, etc.
$I_1 = I_{12} - I_{31}$, etc.

This is an 'integrating' paper. Members are invited to submit papers in this egory, giving the full perspective of the developments leading to the present ıctice in a particular part of one of the branches of electrical science.
Written contributions on papers published without being read at meetings are ited for consideration with a view to publication.
Mr. Skinner is at the Royal Military College of Science.

(1) INTRODUCTION

Discussions on the relative merits of systems for electricity supply metering invariably reveal differences of opinion regarding the physical significance of the terms used. The author has attempted to avoid ambiguity in this respect by reviewing from first principles the definitions of the quantities involved in 3-phase measurements.

Examination of the established literature shows that, although many standard textbooks on electric circuit theory[1,2,3] deal quite comprehensively with the power and energy relations in 3-phase circuits, they make brief reference to the reactive volt-ampere and total volt-ampere relations and the significance of power factor. Likewise, those books dealing with methods of measurement and metering systems[4–8] fail to give an adequate discussion of the ambiguities which can arise under condition of unbalance or asymmetry. Knowlton[9] and Stubbings[10] go a long way to filling this gap, but it is considered that a restatement of the fundamental requirements of metering systems and a comprehensive analysis of the basic metering circuits will help to correlate information which is at present available only in widely scattered references. In particular, the use of symmetrical component analysis enables the circuits for power and reactive volt-ampere measurement to be analysed on a common basis.

Although the author has approached the subject primarily from the point of view of one concerned with the teaching of electrical measurements it is hoped that practising engineers will be interested in the limitations of the metering systems with which they are familiar.

(2) POWER AND REACTIVE VOLT-AMPERES IN SINGLE-PHASE CIRCUITS

The instantaneous power, p, in a single-phase system is equal to the product of the instantaneous voltage, v, and the instantaneous current, i. If the voltage and current are sinusoidal, so that $v = \sqrt{(2)}V \sin(\omega t + \phi)$ and $i = \sqrt{(2)}I \sin \omega t$, then

$$p = vi = VI\cos\phi - VI\cos(2\omega t + \phi) \quad . \quad . \quad (1)$$

If the double-frequency fluctuating component, $VI \cos (2\omega t + \phi)$, is resolved into two components in phase quadrature so that

$$p = VI \cos \phi - VI \cos 2\omega t \cos \phi + VI \sin 2\omega t \sin \phi \quad . \quad (2)$$

then $VI \cos \phi - VI \cos 2\omega t \cos \phi$ is the instantaneous real power and $VI \sin 2\omega t \sin \phi$ is the instantaneous reactive volt-amperes. These quantities are shown in Fig. 1 for the case when $\phi = 30°$.

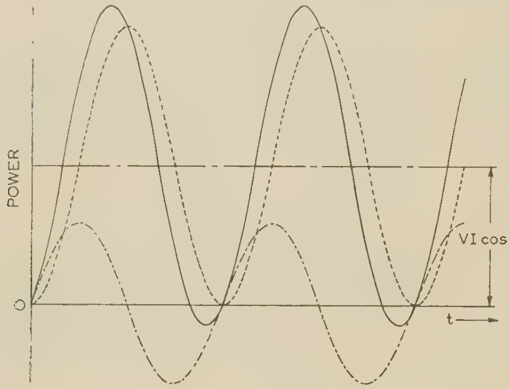

Fig. 1.—Time variation of the components of power in a single-phase circuit for which $\phi = 30°$.

——— Instantaneous power, $VI \cos \phi - VI \cos (2\omega t + \phi)$.
------- Instantaneous real power, $VI \cos \phi(1 - \cos 2\omega t)$.
—·—·— Instantaneous reactive volt-amperes, $VI \sin \phi \sin 2\omega t$.

The instantaneous real power is the component of p in phase with i^2 and transfers energy continuously from the source to the circuit in one direction only. Its mean value, $VI \cos \phi$, is the average power, P. The instantaneous reactive volt-amperes is the component of p in phase quadrature with i^2 and is responsible for an oscillation of energy between the source and the circuit. Its peak value, $VI \sin \phi$, is the reactive volt-amperes, Q.

It is evident that the instantaneous real power and the instantaneous reactive volt-amperes are the values of instantaneous power in the resistance and reactance respectively of the equivalent series circuit.

The total volt-amperes, VI, may be computed from the average power and the reactive volt-amperes by the relation

$$VI = \sqrt{(P^2 + Q^2)} \quad . \quad . \quad . \quad . \quad . \quad (3)$$

Although the above is the accepted method of dividing p into unidirectional and oscillating components it is not the only possible one. Of the infinite number of alternatives an equally logical one is shown in Fig. 2, where the components are both in phase with the fluctuation of p.

The components originally chosen are seen to be arbitrary and hence they have no unique physical significance in terms of unidirectional and oscillating energy flow. It is for this reason that ambiguities arise when summations are made for 3-phase circuits.

(2.1) Phasor Quantities

If the sinusoidal current and voltage are represented by phasor (vector) quantities $\boldsymbol{I} = I\varepsilon^{j\omega t}$ and $\boldsymbol{V} = V\varepsilon^{j(\omega t + \phi)}$, the power and reactive volt-amperes are given by the real and imaginary parts, respectively, of the scalar product of $\boldsymbol{V}$ and $\boldsymbol{I}$:

$$P + jQ = \boldsymbol{V} \cdot \boldsymbol{I} \quad . \quad . \quad . \quad . \quad . \quad . \quad (4)$$

The scalar product is evaluated as the vector product of $\boldsymbol{V}$ and $\boldsymbol{I}^*$, the complex conjugate of $\boldsymbol{I}$.

Thus, $$P + jQ = \boldsymbol{V}\boldsymbol{I}^* \quad . \quad . \quad . \quad . \quad . \quad . \quad (5)$$

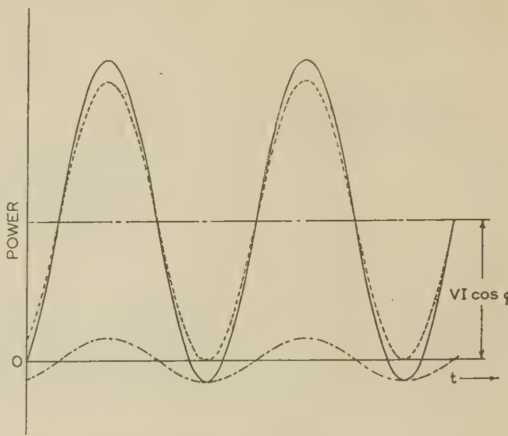

Fig. 2.—Instantaneous power and its alternative unidirectional and oscillating components, $\phi = 30°$.

——— Instantaneous power, $VI \cos \phi - VI \cos (2\omega t + \phi)$.
------- $VI \cos \phi . [1 - \cos (2\omega t + \phi)]$.
—·—·— $VI (\cos \phi - 1) . \cos (2\omega t + \phi)$.

(2.2) Composite Voltages and Currents

If a current and a voltage are each made up of a number of components of the same frequency it is obvious that the sum of the powers due to the individual components must be equal to the total power due to the composite values. It may not be generally realized that a similar relation also holds for the reactive volt-amperes. Thus in a circuit having a voltage $\boldsymbol{V} = \boldsymbol{V}_a + \boldsymbol{V}_b$ and a current $\boldsymbol{I} = \boldsymbol{I}_c + \boldsymbol{I}_d$, the total power and reactive volt-amperes are given by

$$\begin{aligned} P + jQ &= (\boldsymbol{V}_a + \boldsymbol{V}_b)(\boldsymbol{I}_c + \boldsymbol{I}_d)^* \\ &= \boldsymbol{V}_a\boldsymbol{I}_c^* + \boldsymbol{V}_a\boldsymbol{I}_d^* + \boldsymbol{V}_b\boldsymbol{I}_c^* + \boldsymbol{V}_b\boldsymbol{I}_d^* \end{aligned}$$

Therefore

$$\begin{aligned} P + jQ = (&{}_aP_c + {}_aP_d + {}_bP_c + {}_bP_d) \\ &+ j({}_aQ_c + {}_aQ_d + {}_bQ_c + {}_bQ_d) \quad . \quad (6) \end{aligned}$$

This result is useful in computing the power and reactive volt-amperes in a 3-phase system from the symmetrical components of current and voltage.

(2.3) The Influence of Harmonics

The effect of direct and harmonic components in the current and voltage waveforms will now be considered.

Let the instantaneous current and voltage be given by

$$i = I_D + \sqrt{(2)}I_F \sin \omega t + \sqrt{(2)}I_N \sin N\omega t \quad . \quad . \quad . \quad . \quad . \quad (7)$$

$$v = V_D + \sqrt{(2)}V_F \sin (\omega t + \phi_F) + \sqrt{(2)}V_N \sin (N\omega t + \phi_N) (8)$$

The power, reactive volt-amperes and total volt-amperes for the three components individually are given by

D.C.—

$$P_D = V_D I_D \qquad Q_D = 0 \qquad (VA)_D = V_D I_D$$

Fundamental.—

$$P_F = V_F I_F \cos \phi_F \quad Q_F = V_F I_F \sin \phi_F \quad (VA)_F = V_F I_F$$

Harmonic.—

$$P_N = V_N I_N \cos \phi_N \quad Q_N = V_N I_N \sin \phi_N \quad (VA)_N = V_N I_N$$

There is no net transfer of energy between currents and voltages of different frequencies so that the total power is

$$P = P_D + P_F + P_N \quad . \quad . \quad . \quad . \quad . \quad (9)$$

If the total volt-amperes are regarded as the product of r.m.s. tal current and r.m.s. total voltage, then

$$VI = \sqrt{(V_D^2 + V_F^2 + V_N^2)}\sqrt{(I_D^2 + I_F^2 + I_N^2)} \quad . \quad (10)$$

However, if the total reactive volt-amperes, Q, is defined as $Q_D + Q_F + Q_N$, an alternative value of total volt-amperes is

$$\sqrt{[(P_D + P_F + P_N)^2 + (Q_D + Q_F + Q_N)^2]} \quad . \quad (11)$$

It is apparent that this value is not the same as VI.

The two definitions of total volt-amperes give rise to two finitions of power factor:

$$\text{Power factor} = \frac{\Sigma P}{VI}$$

$$\frac{\Sigma P}{\sqrt{[(\Sigma P)^2 + (\Sigma Q)^2]}}$$

It is not possible to say which of the two definitions is prefer-able, but care should be taken that their differences are not nored. A case of particular practical significance is that of sinusoidal voltage with an impure current waveform. P_d, Q_d, P_n and Q_n are then zero, so that

$$\frac{\Sigma P}{VI} = \frac{P_F}{V_F\sqrt{(I_D^2 + I_F^2 + I_N^2)}} \quad . \quad . \quad . \quad . \quad (12)$$

d

$$\frac{\Sigma P}{\sqrt{[(\Sigma P)^2 + (\Sigma Q)^2]}} = \frac{P_F}{V_F I_F} \quad . \quad . \quad . \quad . \quad (13)$$

The former definition of power factor, which is the one nerally adopted, gives a lower value than the latter, which rresponds to the power factor of the fundamental components one.

(3) THREE-PHASE CIRCUITS

(3.1) Power

In a single-phase circuit there is no ambiguity in the definition power, either as an instantaneous or as an average quantity. has a precise physical significance which is universally accepted. similar conformity applies to multiple circuits and to 3-phase stems in particular.

The principle of conservation of energy establishes that the tal power in a complex circuit must be equal to the algebraic m of the powers in the individual branches, and this relation olds for instantaneous and average values. Furthermore, the ower dissipated must be equal to the power supplied. Thus e total power in a 3-phase system can be measured either by mming the powers in the individual phases or by measuring e power transfer along the lines.

(3.2) Reactive Volt-Amperes

It has been shown that the reactive volt-amperes of a single-hase circuit have a somewhat arbitrary physical significance. is not surprising that anomalies arise when an attempt is made combine the individual phase values into an overall value r a 3-phase system.

What idea should be conveyed by the reactive volt-amperes a 3-phase system? An unbalanced unity-power-factor load sults in an oscillating flow of energy whereas a balanced active load has a steady overall energy flow. To relate active volt-amperes to total energy fluctuation would result the anomaly of them being a measure of unbalance rather an of the effect of load reactance.

The accepted concept of total reactive volt-amperes is the gebraic sum of the values for the individual phases. In ection 8.1 it is shown that this definition gives a value which is unique for all 3-phase circuits having the same line current and voltage conditions. The value is the same whether measured in the phases of the source or the load, or from the line quantities.

In the supply industry, interest in a value of reactive volt-amperes is centred round two main requirements. One is the operation of tariff systems which involve a penalty for consumption at low power factor, and the other is the recording of operating conditions when there is an exchange of energy between interconnected power stations. Indirectly, a value of reactive volt-amperes may be used in the operation of volt-ampere demand tariffs, but this is considered later.

The algebraic sum of the phase reactive volt-amperes allows a leading value in one phase to cancel a lagging value in another phase. This is a shortcoming for tariff purposes which is accepted in view of its great advantage of non-ambiguity.

(3.3) Total Volt-Amperes

Three alternative definitions of the total volt-amperes of a 3-phase system are given in B.S. 205. They are:

(*a*) Vector total $= \sqrt{(P^2 + Q^2)}$, where P is the algebraic sum of the active volt-amperes (power) and Q is the algebraic sum of the reactive volt-amperes.

(*b*) Arithmetic total: the sum of the products of the line currents and the corresponding voltages to the neutral point.

(*c*) Equivalent copper-loss total $= V\sqrt{(I_1^2 + I_2^2 + I_3^2 + I_0^2)}$ where V is the line voltage (assumed symmetrical) and I_1, I_2, I_3 and I_0 are the currents in the three lines and neutral.

The three definitions yield the same value under balanced conditions but increasing values in the order (*a*), (*b*), (*c*) in the presence of unbalance. Their suitability as a basis for determining the volt-ampere maximum-demand charge will now be considered.

A consumer should clearly be penalized for unbalanced operation because this reduces the overall power capacity of the supply equipment. Owing to the diversity of unbalanced loading it is unlikely that a particular consumer's unbalance will extend beyond the supply cables and distribution transformers. It is the reduced rating of these, due to the concentration of losses in one phase, which must be compensated for by the tariff system. Since the equivalent copper-loss total volt-amperes is the value most susceptible to increase with unbalance, this appears to be the most suitable for determining the charge.

However, it is seen in Section 8.1 that it is only the vector total definition which is completely unambiguous and which can be evaluated from the line and phase conditions. It is also relatively easy to measure. These two factors tend to outweigh the theoretical advantage of definition (*c*).

The arithmetic total has no merits as a significant physical quantity but it does give a compromise between the other two definitions and might be considered for this reason. Its use as a basis for tariff metering has been advocated by Hill.[17]

(3.4) Power Factor

The overall power factor of a 3-phase system is the ratio of the total power to the total volt-amperes. Clearly there are three possible values depending on the definition of total volt-amperes adopted, and the arguments relating to the merits of the definitions are equally applicable. The type of power-factor meter should, wherever possible, be chosen so that its indications are consistent with the metering system on which the tariff charge is based.

The value based on the vector total definition, i.e. $P/\sqrt{(P^2 + Q^2)}$, has the advantage that it is a measure of reactive loading rather than of unbalance.

(3.5) Symmetrical Components

The representation of unbalanced currents and voltages by their symmetrical components is an established aid in analysis. Further, metering systems have been developed which physically segregate the symmetrical components and give measurements in terms of them.[11]

The relations between the power, reactive volt-amperes and total volt-amperes of the symmetrical components and the actual total values are established in Section 8.2. It is shown that:

(*a*) Net power and reactive volt-amperes are provided only by the interaction of currents and voltages of the same sequence.
(*b*) The total power is the algebraic sum of the powers due to the positive-, negative- and zero-sequence systems.
(*c*) The total reactive volt-amperes is the algebraic sum of those due to the positive-, negative- and zero-sequence systems.
(*d*) In computing the vector total volt-amperes from the symmetrical component quantities the total power and the total reactive volt-amperes must first be evaluated. The value is not given by the sum of the volt-amperes in the three sequence components.

In the particular case of a system with symmetrical voltages, the negative- and zero-sequence power and reactive volt-amperes are zero. The vector total volt-amperes is then equal to that of the positive-sequence components of current and voltage. This is the basis of a meter developed for the measurement of power factor in 3-phase circuits, described in Reference 11.

(4) THE REQUIREMENTS FOR INTEGRATION METERING

The measurement of watt-hours, reactive volt-ampere-hours and total volt-ampere-hours can be made by means of integrating meters whose speeds are proportional to power, reactive volt-amperes and total volt-amperes, respectively. The significance of these integrated values in relation to the requirements of a metering system will now be examined.

The normal energy meter records the net energy consumption, $\int P dt$, where P has an algebraic value depending on the direction of energy flow. Thus it gives equal credit for energy returned by a consumer compared with energy absorbed. Should conditions be such that consumption is during a peak period and the return of energy at an off-peak period, it is obviously desirable that some discrimination should be made. This is normally obtained by the application of a suitable tariff system based on maximum demand, though the use of meters to record separately the energy flow in each direction is a possibility.

In contrast, the value of integrated reactive volt-amperes is the modulus of Q and not the algebraic value. Thus a consumer who operates at a low lagging power factor for one period and a low leading power factor for another will be penalized for both periods on the basis of reactive volt-ampere-hours consumed.

A value of total volt-ampere-hours may be derived from integrating meters sensitive to vector total, arithmetic total or equivalent copper-loss volt-amperes. Alternatively, if the integrated values of watt-hours and reactive volt-ampere-hours are known, an equivalent value of total volt-ampere-hours may be computed. Thus the following expressions for total volt-ampere-hours are possible:

(*a*) $\int \sqrt{(P^2 + Q^2)} dt$
(*b*) $\int$ (Arithmetic total volt-amperes) dt
(*c*) $\int$ (Equivalent copper-loss total volt-amperes) dt
(*d*) $\sqrt{[(\int P dt)^2 + (\int |Q| dt)^2]}$

The arguments concerning the relative merits of (*a*), (*b*) and (*c*) have already been presented in Section 3.3. All three are insensitive to the sign of either P or Q and give values corresponding to the integrated modulus of the volt-amperes. This, in turn, is a measure of the product of the capital equipment utilized and the time for which it is employed—a useful concept for a tariff system.

The value given by (*d*) is not so suitable because it is sensitive to the sign of P and will be reduced by reverse power flow. Also, on flucutating loads, it is low compared with the integrated volt-amperes.

(5) THE METERING OF 3-PHASE SYSTEMS

There appears to have been little attempt in the past to classify the various circuit arrangements suitable for 3-phase metering in terms of the physical quantities actually measured. The analysis of the circuits and discussion of their errors is usually approached in a somewhat haphazard manner. It is hoped that the method of tabulation which follows will help in clarifying this field of supply metering.

The basic principles of the circuits and instruments used are covered by Knowlton[9] and Stubbings.[10] Metering practice on large power systems is discussed in more detail by Henderson[12] and Byrne,[14] while the influence of harmonics on meters and metering systems has been investigated by Dannatt.[13]

(5.1) Watt-Hour Metering

Polyphase energy consumption can be measured by means of a number of separate single-phase watt-hour (cosine) meters or by means of a single multi-element meter. In either case the connections of the meters or elements are the same as those of wattmeters to measure the total power.

These methods of connection fall into two main categories, one which satisfies the requirements of Blondel's theorem for the measurement of total power under any conditions and the other in which certain conditions of symmetry or balance must be assumed for correct registration. Methods in the second category may be used to effect an economy in the number of meters or elements installed.

From the theoretical point of view it is immaterial whether the readings of a number of separate meters are summed algebraically or whether multi-element meters are employed to carry out the summation before integration. However, in practice the errors in registration may be very different for the two methods. For instance, an installation of single-element meters may operate under conditions in which one of them registers in a reverse sense, with consequently larger errors due to friction compensation.

The corresponding multi-element installation would obviate this.

The induction-type meter is used universally for energy measurement and the basic element is available in the following forms:

(*a*) A single element in which one voltage coil is associated with one current coil.
(*b*) A 'half-element' meter in which one voltage coil is associated with two equal current coils.

Table 1 shows the methods of connection using three, two and one meter elements. Diagrams for those methods of which the connections are not apparent from their descriptions are given in Fig. 3. The Table gives, in terms of the symmetrical components, the actual power which the sum of the meter readings will integrate.

Regarding the notation used here, it must be emphasized that the power components involving the interaction of voltage and current of different phase sequence are three times the value for one particular phase, and not the sum of the values for all three phases (which must be zero). For example, in method M 4, the term $_pP_z$ is three times the power due to the positive-

Table 1

CIRCUITS FOR WATT-HOUR METERING

Method of connection			Measured quantity†
Method	Description	Diagram	
M 1	Three meters, phase connected		${}_pP_p + {}_nP_n + {}_zP_z$
M 2	Three meters with voltage and current segregating networks for positive-, negative- and zero-sequence components		${}_pP_p$, ${}_nP_n$, ${}_zP_z$
M 3	Three meters, phase connected, with artificial star point ..		${}_pP_p + {}_nP_n$
M 4	Two meters connected as for 2-wattmeter method	3(*a*)	${}_pP_p + {}_nP_n - {}_pP_z - {}_nP_z$
M 5	Two meters, as M 4, but with star-delta potential transformer		${}_pP_p + {}_nP_n$
M 6	Two meters with segregating networks for positive- and negative-sequence components		${}_pP_p$, ${}_nP_n$
M 7	Two meters with delta-connected current transformers ..	3(*b*)	${}_pP_p + {}_nP_n - {}_zP_p - {}_zP_n$
M 8	Two half-element meters	3(*c*)	${}_pP_p + {}_nP_n - {}_zP_p - {}_zP_n$
M 9	Two meters, delta current transformers and artificial star point		${}_pP_p + {}_nP_n$
M 10	One meter with segregating network for positive-sequence components		${}_pP_p$
M 11	One meter, phase-connected		${}_pP_p + {}_nP_n + {}_zP_z + {}_pP_n + {}_pP_z + {}_nP_p + {}_nP_z + {}_zP_p + {}_zP_n$
M 12	One meter, using combined voltages	3(*d*)	${}_pP_p + {}_nP_n + {}_pP_n + {}_pP_z + {}_nP_p + {}_nP_z$
M 13	One meter, using combined currents	3(*e*)	${}_pP_p + {}_nP_n - {}_pP_n - {}_nP_p$
M 14	One half-element meter	3(*f*)	${}_pP_p + {}_nP_n - {}_pP_n - {}_nP_p$
M 15	One meter, phase-connected, with artificial star point ..		${}_pP_p + {}_nP_n + {}_pP_n + {}_pP_z + {}_nP_p + {}_nP_z$

† ${}_pP_p$, ${}_nP_n$, ${}_zP_z$ = Power due to positive-, negative- and zero-sequence components of voltage and current.
${}_pP_n$, etc. = (Power product of V_p and I_n for one phase) × 3, etc.
The measured quantity given is the power integrated.

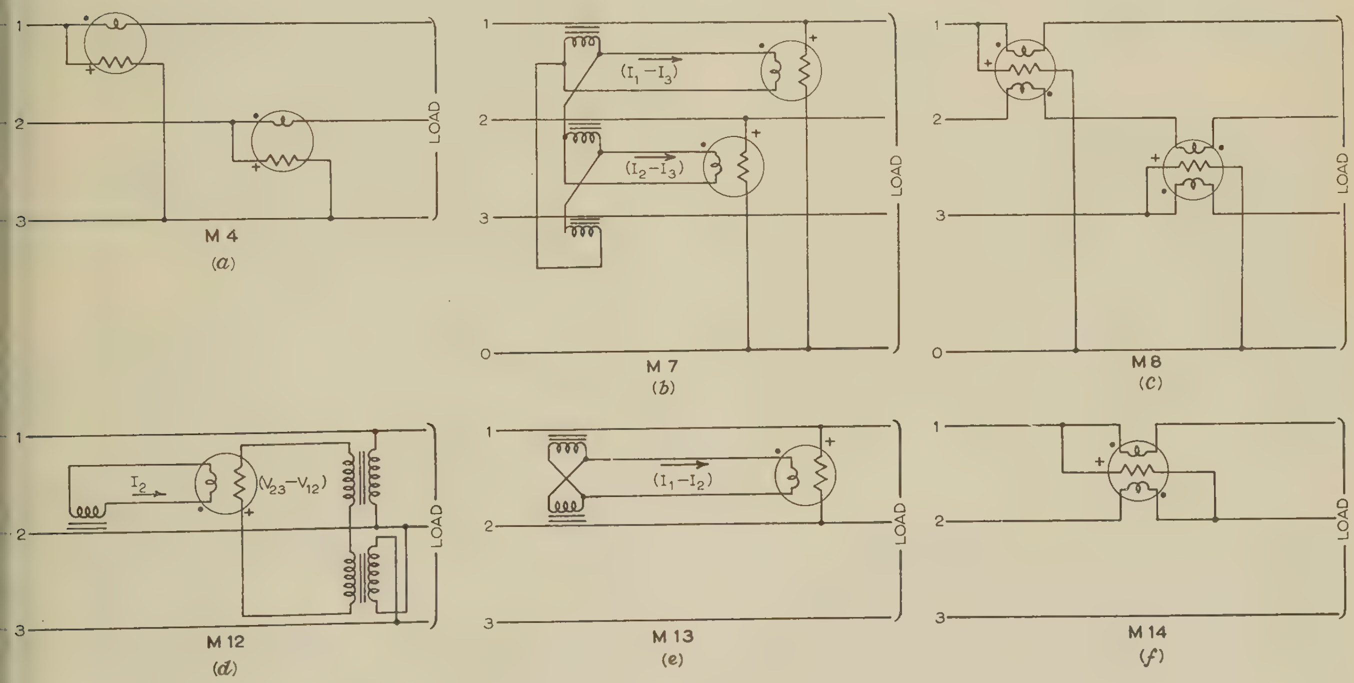

Fig. 3.—Circuits for watt-hour measurement.

The reference is to the corresponding method in Table 1.

equence voltage of phase 3 reacting with the zero-sequence urrent in phase 3, the two meters being connected in lines 1 and 2. In general, the particular phase to which these terms apply is the 'odd phase out' relative to the symmetry of the connections.

The data in Table 1 enable the power components measured under any particular conditions to be derived. For instance, if a system is 3-wire, zero-sequence components of current cannot exist. All terms having the right-hand subscript z will then be zero. The remaining terms give the quantity actually measured. Similarly, if the voltages of a system are symmetrical, the negative- and zero-sequence components of voltage do not exist and all terms having left-hand subscripts n or z will be zero.

Table 2 shows the symmetrical components of power which actually result in energy transfer for the various 3-phase systems. By comparing these with the measured quantities of Table 1

Table 2

COMPONENTS OF POWER WHICH EXIST IN 3-PHASE SYSTEMS

Voltages	Currents	3-wire		4-wire	
		Power	Methods	Power	Methods
Symmetrical	Balanced	${}_pP_p$	M 1–6, 9, 10, 12–15	${}_pP_p$	M 1–15
	Unbalanced	${}_pP_p$	M 1–6, 9, 10	${}_pP_p$	M 1–10
Unsymmetrical	Balanced	${}_pP_p$	M 1–6, 9, 10	${}_pP_p$	M 1–6, 9, 10
	Unbalanced	${}_pP_p + {}_nP_n$	M 1–6, 9	${}_pP_p + {}_nP_n + {}_zP_z$	M 1, 2

The methods referred to are those of Table 1 which will give inherently correct metering in each case.

it can be seen whether a particular method of measurement is suitable for a given system. Those methods of measurement which are inherently correct are indicated in Table 2. In other cases, the difference between the measured quantity and that which actually exists gives the error of the method of measurement.

Suppose, for example, that method M 15 is used on an unsymmetrical unbalanced 3-wire system.

The power which exists is ${}_pP_p + {}_nP_n$.

The power being measured is ${}_pP_p + {}_nP_n + {}_pP_n + {}_pP_z + {}_nP_p + {}_nP_z$.

But since the circuit is 3-wire, I_z is zero and hence ${}_pP_z$ and ${}_nP_z$ are zero. Thus the error is

$$({}_pP_p + {}_nP_n) - ({}_pP_p + {}_nP_n + {}_pP_n + {}_nP_p) = -({}_pP_n + {}_nP_p)$$

The meters will register incorrectly owing to the interaction of positive-sequence voltage with negative-sequence current and negative-sequence voltage with positive-sequence current.

It is of interest to consider which of the methods listed in Table 1 are officially approved for metering purposes. The criterion upon which official approval is based is really enshrined in the 'scope' clause of B.S. 37, Part 4, which excludes meters in which 'the principle of measurement requires balanced conditions of load or supply'. This implies that only those methods which give inherently correct measurement with unsymmetrical voltages and unbalanced currents would be acceptable. Table 2 shows the methods which satisfy this condition for 3-wire and 4-wire circuits.

(5.1.1) **Circuits for Watt-Hour Metering.**

The methods listed in Table 1, together with Fig. 3, are largely self-explanatory. A further note on the use of symmetrical component segregating networks is given to supplement this information.

It may not be realized that some of the standard metering circuits are effective by virtue of symmetrical component segregation. In the two-wattmeter connection M 4, the use of line voltages eliminates the zero-sequence component from the meters. The use of an artificial star point or a star-delta potential transformer also gives voltages from which the zero-sequence component is eliminated. Similarly, the zero-sequence component of current is eliminated in methods using combined currents (M 7, 8, 9, 13, 14).

It is only one stage further to separate the positive- and negative-sequence components of voltage and current and to meter the energy due to each one separately. Each component, being balanced, then requires only a single element for measurement. The main limitation of these methods is that the circuits for separating the components require specific impedance and phase relations and are inherently frequency-sensitive. The non-linearity of meter impedances also limits their use as part of the segregating network.

(5.1.2) **The Effect of Harmonics.**

The performance of the metering circuits in recording energy transfer due to harmonics can be readily deduced. Triplen harmonics have, in effect, zero phase sequence. The 4th, 7th, 10th, 13th, etc., have a positive phase sequence and the 2nd, 5th, 8th, 11th, etc., have a negative phase sequence. Reference to Table 1, which shows which sequence components are measured, therefore also gives the particular harmonics which will produce registration. The correctness of this registration is, of course, dependent on the frequency characteristics of the meters themselves.

(5.2) Reactive Volt-Ampere-Hour Metering

The reactive volt-ampere-hours of a polyphase system can be measured by three basic types of element. These are variations of the induction-type meter and comprise

(*a*) The energy meter element itself.
(*b*) The reactive volt-ampere-hour element.
(*c*) The 60°-lag element.

A reactive volt-ampere-hour element (sine meter) is virtually an energy meter in which the phase angle between the operating fluxes has been changed by 90°. This is generally done by phase-shifting networks in the voltage circuit and the phase relation is consequently frequency-sensitive.

If the phase angle between the fluxes of an energy meter is reduced by 30°, by making the voltage-coil circuit more resistive, then a 60°-lag meter results. The construction, applications and errors of this type of element are discussed by Cheetham,[15] who shows that it has a number of advantages over other types of reactive meter.

If connected to a voltage, V, leading a current, I, by a phase angle, ϕ, the three types of element will integrate, respectively, the values $VI\cos\phi$, $VI\sin\phi$ and $VI\cos(30° + \phi)$.

To comply with the requirement that the algebraic total reactive volt-amperes should be integrated, multi-element meters must be used rather than a number of single-element meters. The modulus value may be derived using two meters, ratcheted against backward registration, which measure leading and lagging reactive volt-ampere-hours separately.

The connections of reactive volt-ampere-hour elements to meter the total value for a 3-phase system correspond exactly to those of energy meters to measure the total watt-hours. Thus all the methods of Table 1 are applicable to reactive metering if suitably modified elements are employed. The use of energy

ters or 60°-lag meters for reactive metering relies upon taining an appropriate phase shift for the operating voltages d currents by cross-phasing of the polyphase circuits. This inherently susceptible to errors in phase relation arising from balance or asymmetry. However, these errors are often less an those of true reactive meters themselves, with the result at cross-phasing methods are commonly employed.

Table 3 gives the circuits which may be used for reactive

(*a*), (*b*) and (*c*) only. The value in definition (*d*) is derived from the registrations of watt-hour and reactive volt-ampere-hour meters.

The process required to meter the vector total volt-ampere-hours is to measure P and Q, resolve these in form $\sqrt{(P^2 + Q^2)}$ and then integrate the resolved value. Normal practice is to derive rotational rates proportional to P and Q from watt-hour and reactive volt-ampere-hour meters, respectively. The resolu-

Table 3

CIRCUITS FOR REACTIVE VOLT-AMPERE-HOUR METERING

Method of connection			Measured quantity†
Method	Description	Diagram	
	Circuits using reactive volt-ampere-hour elements		
R 1-15	As M 1–15 in Table 1 with reactive volt-ampere-hour elements in place of watt-hour elements	See Fig. 3	Substitute Q for P in Table 1
	Circuits using watt-hour elements		
R 16	Three watt-hour meters with voltage and current segregating networks for reactive volt-ampere-hours of positive-, negative- and zero-sequence components		${}_pQ_p,\ {}_nQ_n,\ {}_zQ_z$
R 17	Three watt-hour meters, cross-phase connected to lines ..	4(*b*)	$\frac{1}{\sqrt{3}}({}_pQ_p - {}_nQ_n)$
R 18	Two watt-hour meters with segregating networks for reactive volt-ampere-hours of positive- and negative-sequence components		${}_pQ_p,\ {}_nQ_n$
R 19	Two watt-hour meters with delta current transformers and cross-phase connected to lines	4(*c*)	$\sqrt{3}({}_pQ_p - {}_nQ_n)$
R 20	Two half-element watt-hour meters cross-phase connected to lines		$\sqrt{3}({}_pQ_p - {}_nQ_n)$
R 21	Two watt-hour meters with artificial star point	4(*e*)	$\frac{1}{\sqrt{3}}({}_pQ_p - {}_nQ_n)$
R 22	Two watt-hour meters with phasing auto-transformer ..	4(*f*)	${}_pQ_p - {}_nQ_n$
R 23	Two watt-hour meters connected as for 2-wattmeter method (difference reading)	3(*a*)	$\frac{1}{\sqrt{3}}({}_pQ_p - {}_nQ_n - 2{}_pQ_n + 2{}_nQ_p + {}_pQ_z - {}_nQ_z)$
R 24	One watt-hour meter with segregating networks for VArh of positive-sequence component		${}_pQ_p$
R 25	One watt-hour meter with current of one line and voltage between the other two		$\frac{1}{\sqrt{3}}({}_pQ_p - {}_nQ_n + {}_pQ_n - {}_nQ_p + {}_pQ_z - {}_nQ_z)$
	Circuits using 60°-lag elements		
R 26	Three 60°-lag meters cross-phase connected line/neutral ..	4(*a*)	${}_pQ_p - \frac{\sqrt{3}}{2}{}_nP_n - \frac{1}{2}{}_nQ_n + \frac{\sqrt{3}}{2}{}_zP_z - \frac{1}{2}{}_zQ_z$
R 27	Two 60°-lag meters line connected	4(*d*)	${}_pQ_p - \frac{\sqrt{3}}{2}{}_nP_n - \frac{1}{2}{}_nQ_n - \frac{\sqrt{3}}{2}{}_pP_z + \frac{1}{2}{}_pQ_z - \frac{\sqrt{3}}{2}{}_nP_z + \frac{1}{2}{}_nQ_z$

† The measured quantity given is that integrated by the meters.
${}_pQ_p,\ {}_nQ_n,\ {}_zQ_z$ = Reactive volt-amperes due to the positive-, negative- and zero-sequence components of voltage and current.
${}_pQ_n$, etc. = Reactive volt-amperes due to V_p and I_n for one phase × 3, etc.
${}_pP_n$, etc. = The power product of V_p and I_n for one phase × 3, etc.

etering and the actual quantity which is measured by each one. ne notation is similar to that used in Section 5.1, the left-hand bscripts referring to voltage and the right-hand to currents. here the two subscripts are different the value implied is three nes that for one particular phase. Some explanatory circuit agrams are given in Fig. 4.

The components of reactive volt-amperes present in the various phase systems are given in Table 4, together with the methods measurement which will give inherently correct metering.

The response of the circuits to the reactive volt-amperes of rmonics is given by considering the phase sequence of the rticular frequency components, as in Section 5.1.2.

(5.3) Total Volt-Ampere-Hour Metering

Referring to the four definitions of total volt-ampere-hours ven in Section 4 it is seen that special meters are required for

tion is then performed mechanically by ball-and-disc mechanisms or by differential and ratchet mechanisms. There would appear to be a possible application of electrical computing techniques with resolvers, square-rooting and adding circuits in this field.

The principle of the meters for measurement of arithmetic total volt-ampere-hours is that a watt-hour meter can be converted to a volt-ampere-hour meter if the phase angle between the current and voltage is eliminated or compensation is introduced to neutralize its effect. For a true arithmetic total separate meters must be used in each phase, each one being corrected for its own power factor, and the rotations summed. However, with certain limitations, other less elaborate systems are satisfactory. Baxter[16] describes a recently developed meter which registers the arithmetic total for a system with symmetrical voltages. In this, the arithmetic sum of the rectified line currents controls a saturable reactor, the output of which is a proportional

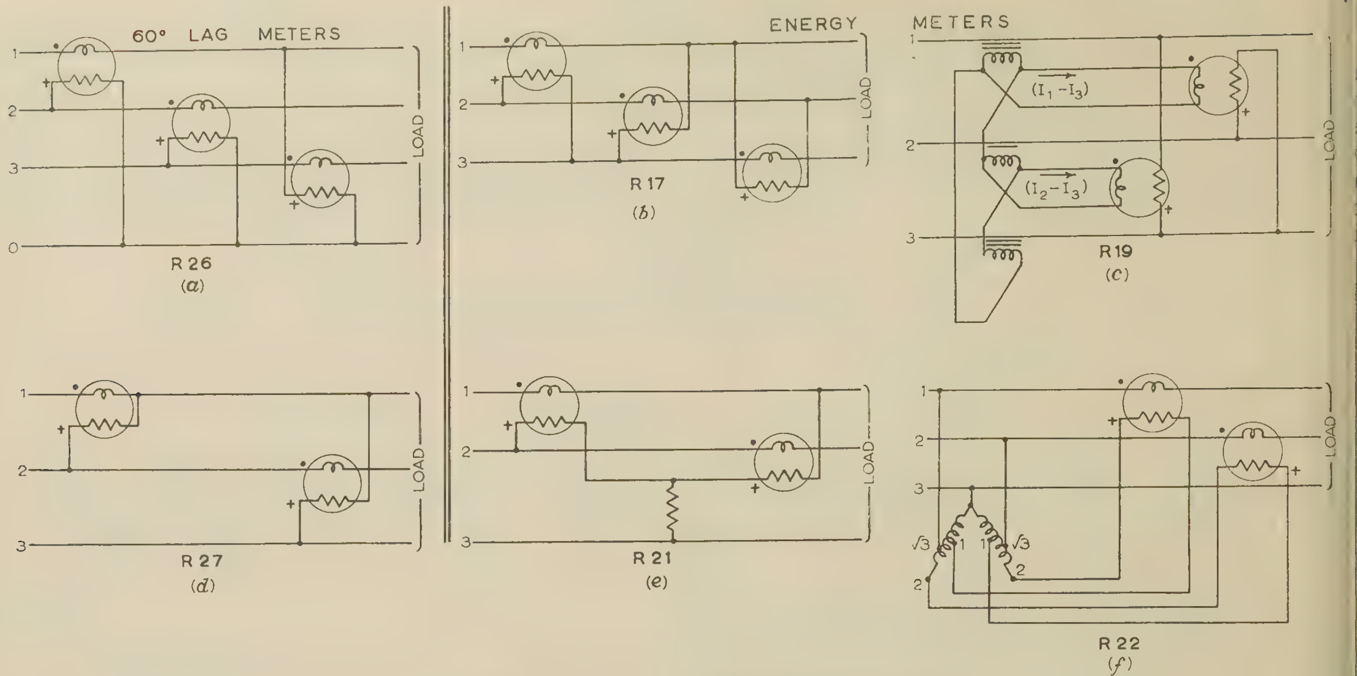

Fig. 4.—Circuits for reactive volt-ampere-hour measurement.

The reference is to the corresponding method in Table 3.

Table 4

Components of Reactive Volt-Amperes which Exist in 3-Phase Systems

Voltages	Currents	3-wire		4-wire	
			Methods		Methods
Symmetrical	Balanced	$_pQ_p$	R 1–6, 9, 10–25, 27	$_pQ_p$	R 1–27
	Unbalanced	$_pQ_p$	R 1–6, 9, 10, 16–22, 24, 27	$_pQ_p$	R 1–10, 16–22, 24, 26
Unsymmetrical	Balanced	$_pQ_p$	R 1–6, 9, 10, 16–22, 24, 27	$_pQ_p$	R 1–6, 9, 10, 16–22, 24, 26, 27
	Unbalanced	$_pQ_p + {}_nQ_n$	R 1–6, 9, 16, 18	$_pQ_p + {}_nQ_n + {}_zQ_z$	R 1, 2, 16

The methods referred to are those of Table 3, which give inherently correct metering in each case.

alternating current. This current and an in-phase voltage proportional to the system voltage operate a watt-hour meter. The registration of this is the time integral of the arithmetic sum of the phase volt-amperes. A number of other phase-elimination meters are described by Knowlton[9] and Stubbings.[10]

No satisfactory meter is available for the measurement of the equivalent copper-loss total volt-amperes although this quantity is physically significant for a tariff system. There is no difficulty in summing the squares of the currents, but the subsequent square-rooting and integration of the resultant presents problems which have not been solved commercially.

(5.4) Maximum Demand Metering

The means by which the maximum demand, in terms of volt-amperes or watts, is measured is beyond the scope of this paper. The relative merits of direct demand meters, integrated demand meters with various demand intervals, and lagged demand meter have been adequately covered elsewhere.[18]

Consideration has already been given in Section 3 to th suitability of the volt-ampere definitions as the basis for assess ment of the kilovolt-ampere-demand charge. Physical signifi cance is not necessarily of first importance since charges ca always be adjusted to give the desired return. However universal agreement on one of the possible methods is ver desirable, and lack of ambiguity is an essential for the on chosen.

(6) CONCLUSIONS

The accepted definitions of total power and total reactiv volt-amperes for a 3-phase system as being the algebraic sum c the individual phase quantities give values which are unam biguous and which can be measured anywhere in the system

adopting the vector total definition for volt-amperes the ne advantages are extended to this quantity.

For the purposes of supply metering the integration of the ;ebraic value of the total power, the modulus of the total ıctive volt-amperes and the vector total volt-amperes gives an equate basis for the operation of any tariff system, particularly ıen coupled with maximum-demand indication. Lack of ıbiguity in definition and measurement is an advantage which tweighs the slightly greater physical significance of some other antities.

The suitability and errors of metering circuits for these antities are readily given by reference to Tables 1–4.

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(8) APPENDICES

(8.1) Power, Reactive Volt-Amperes and Total Volt-Amperes of 3-Phase Systems

Four-Wire Systems.—Consider a 4-wire circuit, which may present a source or a load, with voltages and currents as own in Fig. 5. We have

$$P_1 + jQ_1 = V_1 \bullet I_1 \quad P_2 + jQ_2 = V_2 \bullet I_2 \quad P_3 + jQ_3 = V_3 \bullet I_3$$

ıe total power and reactive volt-amperes are

$$P = P_1 + P_2 + P_3 \text{ and } Q = Q_1 + Q_2 + Q_3$$

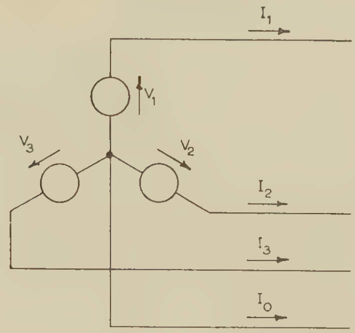

Fig. 5.—Four-wire star circuit.

Clearly, both P and Q are completely specified if the line currents and line/neutral voltages are known. Thus a star source connected by four wires to a star load satisfies the condition that the power and reactive volt-amperes are the same in the source and the load and as measured in the lines.

The vector total volt-amperes for the system is

$$\sqrt{(P^2 + Q^2)} = \sqrt{[(P_1 + P_2 + P_3)^2 + (Q_1 + Q_2 + Q_3)^2]} \quad . \quad (14)$$

The arithmetic total volt-amperes is

$$V_1I_1 + V_2I_2 + V_3I_3 = \sqrt{(P_1^2 + Q_1^2)} + \sqrt{(P_2^2 + Q_2^2)} + \sqrt{(P_3^2 + Q_3^2)} \quad . \quad (15)$$

The equivalent copper-loss volt-amperes is

$$V\sqrt{(I_1^2 + I_2^2 + I_3^2 + I_0^2)} = \sqrt{(P_1^2 + P_2^2 + P_3^2 + Q_1^2 + Q_2^2 + Q_3^2 + V^2I_0^2)} \quad . \quad (16)$$

where V is the line voltage and I_0 the neutral current.

Although the three definitions may give different values they are each unambiguous and completely specified by the line quantities.

Three-Wire Star Systems.—Consider the circuit shown in Fig. 6 where the potentials of the lines and star point are shown relative to some arbitrary reference.

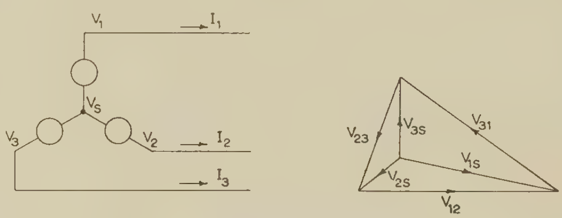

Fig. 6.—Three-wire star circuit.

The total power and reactive volt-amperes are given by

$$P + jQ = (V_1 - V_s) \bullet I_1 + (V_2 - V_s) \bullet I_2 + (V_3 - V_s) \bullet I_3$$
$$= V_1 \bullet I_1 + V_2 \bullet I_3 + V_3 \bullet I_3 - V_s \bullet (I_1 + I_2 + I_3) \quad . \quad . \quad . \quad . \quad (17)$$

Since $I_1 + I_2 + I_3 = 0$, P and Q are independent of the star-point potential, V_s. Thus the phase voltages can have any values and, provided that the line voltages remain unchanged, the total power and reactive volt-amperes will be unaffected. Thus P and Q can be completely specified by the line currents and voltages and will have the same values in either a source or a load.

Since the vector total volt-amperes is defined in terms of P and Q only, this will also be the same for source, load or lines.

The arithmetic total volt-amperes is

$$|V_1 - V_s|I_1 + |V_2 - V_s|I_2 + |V_3 - V_s|I_3 \quad . \quad . \quad (18)$$

This can have any value, for any given line voltages, depending on the star-point potential, V_s. Thus it can be different in the source and in the load and cannot be specified from the line quantities.

The equivalent copper-loss total volt-amperes is defined in terms of the line quantities and so has a single value only.

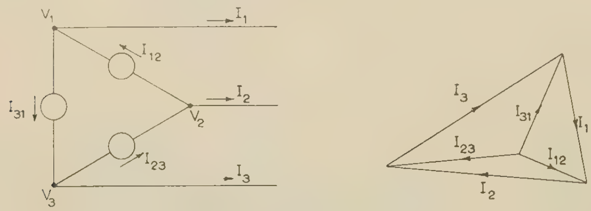

Fig. 7.—Delta circuit.

Three-Wire Delta Systems.—Consider the delta circuit shown in Fig. 7. The total power and reactive volt-amperes are given by

$$P + jQ = (V_1 - V_2) \bullet I_{12} + (V_2 - V_3) \bullet I_{23} + (V_3 - V_1) \bullet I_{31}$$

Now $I_1 = I_{12} - I_{31}$, etc.

Hence, $$P + jQ = V_1 \bullet I_1 + V_2 \bullet I_2 + V_3 \bullet I_3 \quad . \quad . \quad (20)$$

Thus the phase currents can have any values, and, provided that the line currents remain unchanged, the total power and reactive volt-amperes will be unaffected. Also P and Q can be completely specified by the line quantities.

As before, the vector total volt-amperes has a single value for a source, a load or as measured in the lines.

The arithmetic total volt-amperes, which depends on the modulus of the phase currents, can have any value depending on the position of the star point of the phase-current vectors. The equivalent copper-loss total is defined as before by the line currents and voltages and has a single value.

In conclusion, it is seen that the total power and reactive volt-amperes in any 3-phase system can be specified by the line currents and voltages. Hence the vector total volt-amperes is also so specified and has a single value whether measured in the source, the load or the lines. The arithmetic total varies with the phase conditions and the equivalent copper-loss total cannot be measured from the phase quantities only.

(8.2) Symmetrical Components

The subscripts p, n and z indicate the positive-, negative- and zero-sequence components and subscripts 1, 2 and 3 represent the phases of a 3-phase system.

The currents in the system are

$$I_1 = I_p + I_n + I_z \quad . \quad . \quad . \quad . \quad . \quad . \quad (21)$$

$$I_2 = a^2 I_p + aI_n + I_z \quad . \quad . \quad . \quad . \quad . \quad (22)$$

$$I_3 = aI_p + a^2 I_n + I_z \quad . \quad . \quad . \quad . \quad . \quad (23)$$

where $$a \equiv \angle 120^\circ \equiv -1/2 + j(\sqrt{3})/2$$

The corresponding phase voltages are

$$V_1 = V_p + V_n + V_z \quad . \quad . \quad . \quad . \quad . \quad . \quad (24)$$

$$V_2 = a^2 V_p + aV_n + V_z \quad . \quad . \quad . \quad . \quad (25)$$

$$V_3 = aV_p + a^2 V_n + V_z \quad . \quad . \quad . \quad . \quad (26)$$

The power and reactive volt-amperes for phase 1 are given by

$$P_1 + jQ_1 = (V_p + V_n + V_z) \bullet (I_p + I_n + I_z) \quad . \quad (27)$$

Similarly

$$P_2 + jQ_2 = (a^2 V_p + aV_n + V_z) \bullet (a^2 I_p + aI_n + I_z) \quad . \quad (28)$$

$$P_3 + jQ_3 = (aV_p + a^2 V_n + V_z) \bullet (aI_p + a^2 I_n + I_z) \quad . \quad (29)$$

Multiplying out the right-hand side of these equations and adding gives

$$P + jQ = 3V_p \bullet I_p + 3V_n \bullet I_n + 3V_z \bullet I_z \quad . \quad . \quad (30)$$

Note that, for example,

$$a^2 V_p \bullet a^2 I_p = a^2 V_p (a^2 I_p)^* = a^2 V_p a I_p^*$$
$$= a^3 V_p I_p^* = V_p \bullet I_p$$
$$a^2 V_p \bullet aI_n = a^2 V_p (aI_n)^* = a^2 V_p a^2 I_n^*$$
$$= aV_p I_n^* = aV_p \bullet I_n$$

Since $1 + a + a^2 = 0$, all terms involving products of voltages and currents of different phase sequence are zero.

Eqn. (30) shows that the total power and the total reactive volt-amperes are equal to the algebraic sum of the values for the individual sets of symmetrical components. Thus

$$P = P_1 + P_2 + P_3 = {}_pP_p + {}_nP_n + {}_zP_z \quad . \quad . \quad (31)$$

and $$Q = Q_1 + Q_2 + Q_3 = {}_pQ_p + {}_nQ_n + {}_zQ_z \quad . \quad (32)$$

where $${}_pP_p + j_pQ_p = 3V_p \bullet I_p, \text{ etc.} \quad . \quad . \quad . \quad . \quad (33)$$

Volt-Amperes.—The total volt-amperes of the positive-, negative- and zero-sequence components are, respectively, $3V_pI_p$, $3V_nI_n$ and $3V_zI_z$.

The vector total volt-amperes for the 3-phase system is

$$\sqrt{(P^2 + Q^2)} = \sqrt{[({}_pP_p + {}_nP_n + {}_zP_z)^2 + ({}_pQ_p + {}_nQ_n + {}_zQ_z)^2]} \quad . \quad . \quad . \quad . \quad (34)$$

Thus symmetrical-component segregating networks, which enable the power and reactive volt-amperes in the sequence components to be measured, can be used for computing the vector total.

It should be noted that the value is not the sum of the volt-amperes of the three sequence components, which is

$$\sqrt{({}_pP_p^2 + {}_pQ_p^2)} + \sqrt{({}_nP_n^2 + {}_nQ_n^2)} + \sqrt{({}_zP_z^2 + {}_zQ_z^2)}$$

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HE PERFORMANCE OF DISPLACEMENT GOVERNORS UNDER STEADY-STATE CONDITIONS

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SUMMARY

The method of speed control most generally used at the present ıe relies upon the centrifugal governor which controls the power mitted to a driving machine, generally a prime mover, in relation the difference between the speed of the machine shaft and a selected sic or no-load speed.

Other methods of control are, however, possible, and one which pears to have certain advantages is that in which the power input is ıtrolled in relation to the angular displacement between the machine ıft and another shaft which rotates at a defined and constant angular ocity. This has been called displacement governing, and an attempt nade here to investigate the performance of displacement governors en controlling the power supply to turbo-alternators working in the ady state.

The performance of such governors under transient conditions has eady received attention, but as far as the present authors are aware, steady-state performance has not been explicitly treated before.

LIST OF SYMBOLS

C = Centrifugal governor droop, watts/rad/sec.
f = Frequency of network under load conditions, c/s.
f_0 = Frequency corresponding to no-load speed of the machine, c/s.
H = Machine inertia constant, i.e. the ratio of energy stored in the rotating parts at synchronous speed to the rated power, kW-sec per kW.
I_d, I_q = Active and reactive currents, respectively, amp.
I, I_L = Machine and load currents, respectively, amp.
K = Displacement governor gain, watts/rad.
P_e = Electrical output power, watts.
P_f = Full-load (rated) power, watts/phase.
P_i = Mechanical input power, watts.
$P_s = dP_e/d\theta$ = Synchronizing-power coefficient, watts/rad.
$P_T = P_i - P_e$ = Accelerating power, watts.
R_a, X_a = Armature resistance and reactance, respectively, ohms.
$_L, X_L, Z_L$ = Load resistance, reactance and impedance, respectively, ohms.
V = Generated e.m.f., volts.
V_0 = Terminal voltage, volts.
$_1\angle\phi_{11}, Z_{22}\angle\phi_{22}$ = Driving-point impedances of the two machines respectively, ohms.
$Z_{12}\angle\phi_{12}$ = Transfer impedance between the two machines, ohms.
α = Angle between machine rotor and absolute.
α_0 = Angular shift of the reference vector from the absolute.
θ = Power angle, i.e. angle between V and V_0.
ω = Electrical angular velocity, rad/s.

Voltages, currents, powers and impedances are per phase. All angles are in electrical radians unless otherwise stated.
1, 2, . . . n = Number of machines in question.

(1) INTRODUCTION

The paper represents an attempt to define the performance of a type of governor which has lately attracted some attention. Its action is investigated here in relation to the steady-state operation and load-sharing characteristics of turbo-alternator sets working under the control of this type of governor to supply a synchronous network.

The term 'displacement governor' is used to define a mechanism by means of which the power input to a machine is controlled as a function of the angular displacement between two vectors, one rotating at a standard constant angular velocity, and the other with the angular velocity of the machine shaft.

In Fig. 1, if OS is the vector representing the standard angular

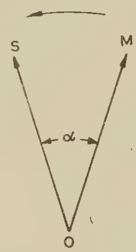


Fig. 1.—Rotating vectors representing standard angular velocity and machine rotor.

velocity and OM that representing the angular velocity of the machine shaft, the governor will operate to make the power input to the machine a function of the retardation angle α. For simplicity a linear function may be assumed and we may write:

$$P_i = K\alpha \quad . \quad . \quad . \quad . \quad . \quad . \quad . \quad (1)$$

where α is taken as positive for an angle of lag. K, which may be called the governor gain, is measured in watts per radian and relates power input to angular deflection.

It will be clear that under the control of such a governor the governed machine will respond to an increase in load demand by falling back with respect to the standard vector until the displacement angle has increased by the amount required to give an increase in power input sufficient to supply the increase in load demand. When this adjustment has been accomplished the machine will settle down to run with the new angle of lag which, in the absence of further changes of load demand, will remain constant. Thus, under steady-state conditions the angular velocity of the machine shaft will at all times be identical with the standard speed. For this reason the term 'synchronous governing'[1,2] is sometimes applied to this system of speed control; it has also been treated under the titles 'time-error'[3] and 'load-angle' governing.[4–6]

Vritten contributions on papers published without being read at meetings are ited for consideration with a view to publication.
Emeritus Professor Prescott, formerly Professor of Electrical Engineering, King's llege, University of Durham, is now with the English Electric Co. Ltd.
Dr. El-Kharashi is with A. Reyrolle and Co. Ltd., on study leave from Ain-Shams iversity, Egypt.

It is not necessary that the power input shall be a function of the whole angle of displacement; it may in some cases be more convenient to relate the input to the angle between the shaft vector and some reference vector which rotates with, but is deflected by a constant angle from, the standard vector. Thus, in Fig. 2, OS represents the standard vector, OR the

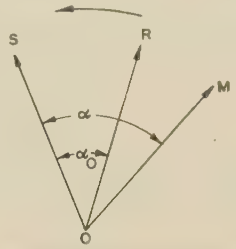


Fig. 2.—Rotating vectors representing standard angular velocity, reference vector and machine rotor.

reference vector displaced from the standard by the constant angle α_0, and OM the machine vector displaced from the standard by the angle α which will vary with load. We now arrange that the power input, P_i, shall be a linear function of the angle $\alpha - \alpha_0$ between the machine vector and the reference vector. If the machine losses are neglected, the input P_i will be equal to the output P_e, and for steady-state conditions we can write

$$P_i = K(\alpha - \alpha_0) = P_e \quad . \quad . \quad . \quad . \quad (2)$$

If P_e is zero the angular deviation, $\alpha - \alpha_0$, must be zero and the machine vector will coincide with the reference vector. Any increase in P_e will cause the machine vector to fall back from the reference vector until equilibrium is again established, but as in the previous case the machine speed will always be identical with the standard speed, except during periods of load change.

In drawing the vector diagram for a single machine supplying a dead load it is convenient to take the e.m.f. vector OV as the machine vector (see Fig. 3) which will be separated from the terminal-voltage vector OV_0 by the load angle θ.

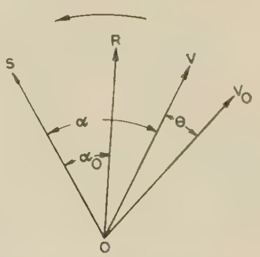


Fig. 3.—Vector diagram of a single machine supplying a dead load.

It thus appears that the displacement governor operates to maintain a constant speed under all conditions of steady load that are within the capacity of the governed machine and that changes of load are met as the result of changes in the angular deviation between the machine and reference vectors; furthermore, because the power input is a (linear) function of this deviation, the displacement governor endows the machine with a synchronizing tendency, thus providing it, in effect, with a synchronizing torque.

(2) SMALL TURBO-ALTERNATOR SET WORKING IN PARALLEL WITH A LARGE NETWORK CARRYING A DEAD LOAD

The general arrangement of a small turbo-generator set working in parallel with a network supplied by a number of large sets

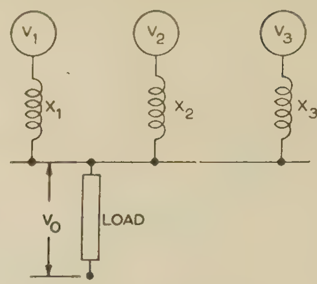


Fig. 4.—Small machine working in parallel with a large network and carrying a dead load.

and carrying a dead load is shown in Fig. 4. Machine 1 is small having armature reactance X_1 and open-circuit e.m.f. V_1; X_2, X_3, . . . and V_2, V_3 . . . are the corresponding quantities for the large machines, armature resistance being neglected in each case.

If all the sets are controlled by displacement governors, then in the steady state the network frequency will be the same as the standard frequency and the vector diagram for the small generator may be drawn as in Fig. 5: here vector OV_0 represents

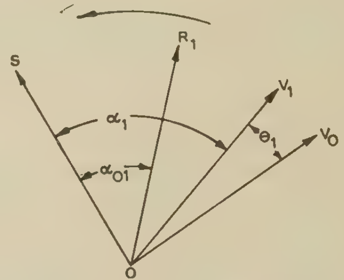


Fig. 5.—Vector diagram of a small machine working in parallel with a large network and carrying a dead load.

the terminal voltage of the small alternator, but this is also the voltage of the network and its vector rotates with the same angular velocity as the standard and reference vectors OS and OR_1. Since the set under consideration is small compared with the other sets, perturbations in its electrical load may be regarded as having a negligible effect upon the magnitude of OV_0 and upon its angular position in relation to OS and OR_1. Thus the angle $\theta_1 + \alpha_1$ and the length of OV_0 may be assumed constant and thus

$$(\alpha_1 - \alpha_{01}) + \theta_1 = \text{constant} = \beta_1 \text{ (say)} \quad . \quad . \quad . \quad (3)$$

The electrical power output of machine 1 may therefore be written as

$$P_{e1} = \frac{V_1 V_0}{X_1} \sin \theta_1 \quad . \quad . \quad . \quad . \quad . \quad (4)$$

and the input power as

$$P_{i1} = K_1(\alpha_1 - \alpha_{01}) = K_1(\beta_1 - \theta_1) \quad . \quad . \quad . \quad (5)$$

If losses are neglected the output must be equal to the mechanical input, so we write

$$K_1(\beta_1 - \theta_1) = \frac{V_1 V_0}{X_1} \sin \theta_1 \quad . \quad . \quad . \quad . \quad (6)$$

For steady-state conditions $P_{T1} = P_{i1} - P_{e1}$ must vanish and eqn. (6) may be exhibited graphically as in Fig. 6, where it can be seen that for each value of $\alpha_1 - \alpha_{01}$ less than $V_1 V_0 / K_1 X_1$, two values of θ_1 will satisfy the equation. It remains to determine whether these values imply conditions of stable operations.

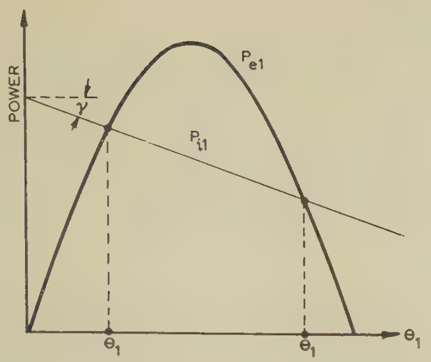


Fig. 6.—Graphical solution of eqn. (6).

$\tan\gamma = K_1$

$P_{e1} = \dfrac{V_1V_0}{X_1}\sin\theta_1$

$P_{i1} = K_1(\beta_1 - \theta_1)$

In order that the machine may be stable the total synchronizing ower coefficient, defined as $dP_{T1}/d\theta_1$, must be positive; thus

$$\frac{dP_{T1}}{d\theta_1} = \frac{V_1V_0}{X_1}\cos\theta_1 + K_1 > 0 \quad . \quad . \quad . \quad (7)$$

r stable operation. This condition will be fulfilled so long as $_1V_0/K_1X_1 \cos\theta_1 > -1$ and will be fulfilled over the range $= 0$ to π if $V_1V_0/K_1X_1 = 1$. For this value, $K_1 = V_1V_0/X_1 =$ $_{,max}$, synchronous operation is possible and stable over both e rising and falling portions of the power/load-angle curve, r, as has been stated above, the displacement governor endows e governed machine with an additional synchronizing torque ver and above that associated with its displacement relative the system-voltage vector, and can extend the working range y 90° as compared with the same machine when controlled y a centrifugal governor.

) TWO TURBO-ALTERNATOR SETS CONTROLLED BY DISPLACEMENT GOVERNORS AND WORKING IN PARALLEL TO SUPPLY A DEAD LOAD

Let the load consist of the series combination R_L and X_L ee Fig. 7), and let the armature resistances of the alternators

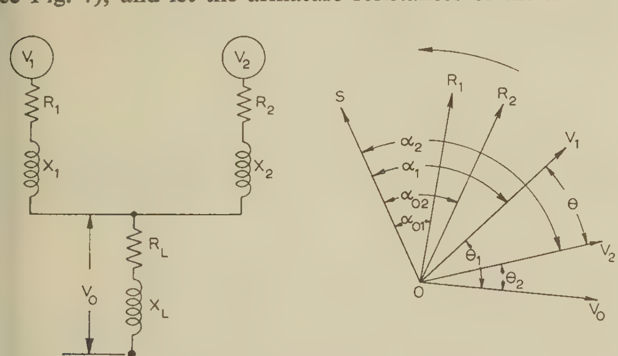


Fig. 7.—Two alternators working in parallel and supplying a dead load.

e R_1 and R_2, respectively. For the turbine sides we assume overnor gains K_1 and K_2, and the angular shift of the references om the absolute α_{01} and α_{02} respectively.

For steady-state conditions, the power of the two alternators given by

$$P_1 = K_1(\alpha_1 - \alpha_{01}) = \frac{V_1^2}{Z_{11}}\cos\phi_{11} - \frac{V_1V_2}{Z_{12}}\cos(\phi_{12} + \theta) \quad (8)$$

$$P_2 = K_2(\alpha_2 - \alpha_{02}) = \frac{V_2^2}{Z_{22}}\cos\phi_{22} - \frac{V_1V_2}{Z_{12}}\cos(\phi_{12} - \theta) \quad (9)$$

where $\theta = \theta_1 - \theta_2 = \alpha_2 - \alpha_1$

Solving for θ, it is shown in Section 7.1 that the two equations give

$$(\alpha_{02} - \alpha_{01}) - A - \theta = BC\sin(\theta - \lambda) \quad . \quad . \quad (10)$$

in which
$$A = \frac{V_1^2}{K_1Z_{11}}\cos\phi_{11} - \frac{V_2^2}{K_2Z_{22}}\cos\phi_{22}$$

$$B = \frac{V_1V_2}{Z_{12}}$$

$$C^2 = \left(\frac{1}{K_1} + \frac{1}{K_2}\right)^2 - \frac{4}{K_1K_2}\cos^2\phi_{12}$$

$$\tan\lambda = \frac{K_2 - K_1}{K_2 + K_1}\cot\phi_{12}$$

Eqn. (10) may be solved by plotting the right- and left-hand sides against θ and finding the points at which the straight line and sine curve intersect, as at P_1, P_1', P_2, P_2', etc., in Fig. 8.

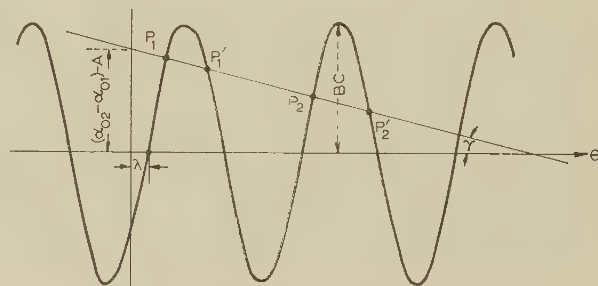


Fig. 8.—Graphical solution of eqn. (10).

$\tan\gamma = 1$

It is shown in Section 7.2 that of these points of intersection only those on the rising parts of the sine curve represent conditions of stable operation. It is to be noted also that any points of intersection implying motoring conditions for either of the alternators can have no meaning when those machines are driven by prime movers.

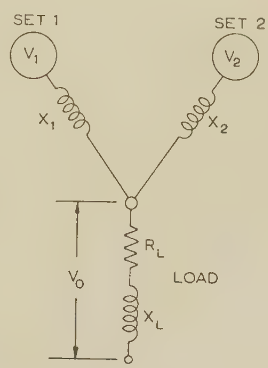


Fig. 9.—Two sets working in parallel to supply a dead load.

(3.1) Division of Load

It is convenient to consider now the division of load between machines controlled by displacement governors, since this may be illustrated with reference to the two-machine case and com-

pared with the division which would occur under the influence of centrifugal governors.

In the case of two turbo-alternators whose throttle valves are controlled by centrifugal governors, and which work in parallel to supply a dead load, the proportion of the total load taken by each will be determined, if turbine losses are neglected, by four quantities, namely the governor droops and the no-load speeds of the two sets. Having defined these quantities, there can be only one mode in which the total load will divide itself between the two sets for steady-state operation.

The power of the machines may be written as

$$P_1 = C_1(f_{01} - f) = \frac{V_1^2}{Z_{11}} \cos \phi_{11} - \frac{V_1 V_2}{Z_{12}} \cos (\phi_{12} + \theta) \quad (11)$$

$$P_2 = C_2(f_{02} - f) = \frac{V_2^2}{Z_{22}} \cos \phi_{22} - \frac{V_1 V_2}{Z_{12}} \cos (\phi_{12} - \theta) \quad (12)$$

Under steady-state conditions, θ and all other quantities on the right-hand side are assumed to be independent of the other variable f, and thus, for any given value of f, the ratio

$$\frac{P_1}{P_2} = \frac{C_1(f_{01} - f)}{C_2(f_{02} - f)} \quad . \quad . \quad . \quad . \quad . \quad (13)$$

is explicitly defined. The ratio of the right-hand sides of eqns. (11) and (12) is therefore fixed for a given value of f and, whatever may be the values of the electrical constants, the angle θ will adjust itself to give the ratio required.

If the sets are controlled by displacement governors the division of load will depend upon the values of nine constants. Of these, four are characteristics of the governors themselves and may be styled the 'mechanical' quantities. They are:

(*a*) The governor gains, K, which may be regarded as analogous to the droops in the centrifugal case.

(*b*) The phase angles of the reference vectors, α_0, which may be regarded as the analogous of the no-load frequencies in the centrifugal case.

If, however, eqns. (8) and (9) for displacement governing are examined, it is seen that the right-hand sides contain non-linear functions of the two variables α_1 and α_2 while the left-hand sides contain linear functions of the same variables. It therefore follows that the division of load will be conditioned not only by the 'mechanical' constants but by all the 'electrical' constants, i.e. by V_1, V_2, Z_{11}, Z_{22}, Z_{12} as well, and that a change in any of these will affect the load distribution. It is possible, for instance, to transfer load from one set to another by increasing the excitation of the one or reducing the excitation of the other.

(3.2) Multiple Solutions

Since the right-hand sides of eqns. (8) and (9) contain periodic functions of α_1 and α_2 it is to be expected that multiple solutions of the equations may exist for steady-state operation. These solutions are defined by the points P_1, P_2, etc., of Fig. 8 and imply that the power ratio P_1/P_2 may have a number of values each of which corresponds to a certain value of the angular separation θ between the machine e.m.f.'s. The successive values of the ratio are associated with successive increments of θ, each having a different value but always fulfilling the condition $\alpha_1 + \theta_1 = \alpha_2 + \theta_2$. Each increment is occasioned by pole slipping on the part of one or other of the alternators, but it is to be noticed that after each increment has been established the sets will operate with the new division of load in a perfectly stable manner and at a speed identical with that of the standard vector.

The actual angular displacement 'chosen' by the alternators will be determined by dynamical considerations which are influenced, among other things, by the magnitude and mode of application of the electrical load (a subject which we hope to treat elsewhere).

(3.3) Example

Perhaps the best way of demonstrating the operation of displacement governors is by referring to a specific example, and the case has been worked out for two turbo-alternator sets which operate in parallel to supply a dead load consisting of a resistance of 3·2 ohms per phase in series with a reactance of 2·4 ohms per phase. The particulars of the sets are:

	Set 1	Set 2
Governor gain, K, watts/rad	6 000	4 000
Phase-shift angle, α_0	0	0
Generated e.m.f., V, volts/phase	1 500	800
Armature reactance, X, ohms/phase ..	12·5	8

and the circuit arrangement is shown in Fig. 9.

Neglecting armature resistance, the equation which must be satisfied is

$$0{\cdot}011\,63 - 0{\cdot}001\,62\theta = \sin(\theta - 6°\,26')$$

where θ is in electrical degrees.

The results derived are shown in Table 1.

Table 1

θ	Load on set 1	Load on set 2	Total load	Load voltage, V_o	θ_1	α_1	θ_2	α_2	$\theta_1 + \alpha_1$	$\theta_2 + \alpha_2$
	kW/phase	kW/phase	kW/phase	volts/phase						
6° 30′	34·55	23·48	58·03	538	32° 21′	330°	25° 55′	336° 30′	362° 21′	362° 25′
334° 23′	19·2	36·2	55·4	526	377° 42′	183° 30′	43° 33′	518°	561° 12′	561° 33′
−321° 22′	44·65	7·26	51·91	510	46° 43′	426°	368° 6′	104° 30′	472° 43′	472° 36′

(3.3.1) Effect of Governor Gain.

If the governor gain of set 2 is increased by 50%, making $K_1 = K_2$, all other constants remaining unchanged, the equation for solution becomes

$$-0{\cdot}1023 - 0{\cdot}002\,04\theta = \sin\theta$$

θ being expressed in electrical degrees as before.

The results derived are shown in Table 2.

It is seen that while the total load is little affected as between Tables 1 and 2, the proportion carried by set 2 is increased in the second case. This is, of course, to be expected, since the sensitivity of the second governor has been increased in relation to that of the first.

(3.3.2) Effect of Changes in Relative Phase Shift of the Reference Vectors.

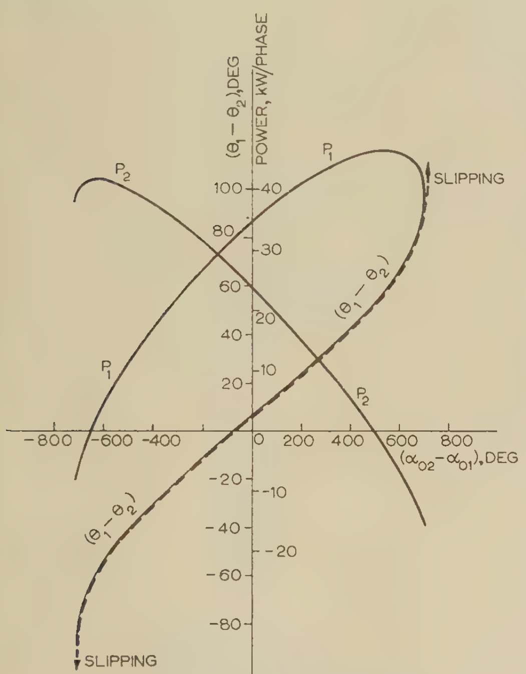
Taking $K_1 = 6\,\text{kW/rad}$, $K_2 = 4\,\text{kW/rad}$, $V_1 = 1\,500$ volts/phase and $V_2 = 800$ volts/phase, we can write the equation for the relative phase shift as

$$\alpha_{02} - \alpha_{01} = -7{\cdot}2 + \theta + 615\sin(\theta - 6°\,26')$$

Table 2

θ	Load on set 1	Load on set 2	Total load	Load voltage, V_o	θ_1	α_1	θ_2	α_2	$\theta_1 + \alpha_1$	$\theta_2 + \alpha_2$
	kW/phase	kW/phase	kW/phase	volts/phase						
$-5°$ 15′	29·33	28·78	58·11	539	26° 58′	279° 42′	32° 12′	274° 24′	306° 40′	306° 36′
312° 20′	8·01	40·78	48·79	494	367° 47′	76° 30′	55° 38′	388° 42′	444° 17′	444° 20′
$-325°$ 50′	43·65	9·55	53·2	516	44° 50′	417°	370° 40′	91° 10′	461° 50′	461° 50′

ere all angles are in electrical degrees, and obtain the results hibited in the curves of Fig. 10 which show the load distribu-n up to the first incidence of pole slipping and indicate the ssibility of transferring load between the sets by altering the ase shift of either reference with respect to the common solute vector.



. 10.—Variation of the angular separation between the rotors and the power generated by each machine with the relative shift of the reference vectors.

3.3) Effect of Excitation.

f, maintaining the values of the governor gains as in the pre-us example, the generated e.m.f. of set 2 is increased by 25%, ing $V_1 = 1{\cdot}5$ kV/phase and $V_2 = 1$ kV/phase, we obtain the uation

$$0{\cdot}1274 - 0{\cdot}001\,3\theta = \sin(\theta - 6°\ 26')$$

ere θ is in electrical degrees, and derive the results shown in ble 3.

If Table 3 is compared with Table 1 it is seen that change in the excitation of one machine, all other parameters remaining unaltered, affects the distribution of load as between the two sets, though it is to be noticed that increasing the excitation of a given set does not imply that this set will of necessity take a larger proportion of the total load.

(3.3.4) Multiple Solutions.

Tables 1–3 show that there are a number of values of the angles θ_1, θ_2, α_1, and α_2 with which the sets can operate in the steady state. In Tables 1 and 2 there are three values of each of these angles for which steady-state operation is possible. In Table 3 there are five values of each angle, the last set of which is inadmissible as it implies a negative output (i.e. motoring action) for the generator of set 2 to the extent of 10·2 kW/phase. This could not occur in the case of turbo-alternators unless the motoring power were sufficiently small to be absorbed by the losses of the set.

(4) GENERAL CASE OF n MACHINES

If the number of machines is greater than two an approximate solution may be obtained, if armature resistances are neglected, by transferring the power equations into polar co-ordinates. First, assume that the reference vectors are not shifted from the absolute, i.e. $\alpha_{01} = \alpha_{02} = \ldots = \alpha_{0n} = 0$. The equations which must be satisfied are

$$\left.\begin{aligned} \alpha_1 &= \frac{V_1 V_0}{K_1 X_1} \sin\theta_1 \\ \alpha_2 &= \frac{V_2 V_0}{K_2 X_2} \sin\theta_2 \\ &\cdots\cdots \\ \alpha_n &= \frac{V_n V_0}{K_n X_n} \sin\theta_n \end{aligned}\right\} \qquad (14)$$

$$\Sigma\frac{V}{X}\sin\theta = \frac{R_L}{Z_L^2}V_0 \qquad (15)$$

$$\frac{\Sigma\dfrac{V}{X}\cos\theta}{\Sigma\dfrac{V}{X}\sin\theta} = \frac{X_L + Z_L^2\Sigma\dfrac{1}{X}}{R_L} \qquad (16)$$

$$\theta_1 + \alpha_1 = \theta_2 + \alpha_2 = \ldots = \theta_n + \alpha_n \qquad (17)$$

(see Section 7.4).

Table 3

θ	Load on set 1	Load on set 2	Total load	Load voltage, V_o	θ_1	α_1	θ_2	α_2	$\theta_1 + \alpha_1$	$\theta_2 + \alpha_2$
	kW/phase	kW/phase	kW/phase	volts/phase						
31° 15′	42·25	29·05	71·3	597	36° 9′	403°	22° 50′	416° 30′	439° 9′	439° 20′
348° 1′	28·25	43·1	71·35	597	383° 17′	269°	35° 17′	617°	652° 17′	652° 17′
678° 8′	9·42	53·6	63·02	561	728° 3′	90°	49° 49′	768°	818° 3′	817° 49′
$-320°$ 3′	51·75	12·06	63·81	565	49° 49′	493°	369° 51′	173°	542° 49′	542° 51′
$-638°$ 40′	51·65	$-10{\cdot}2$	41·45	455	71°	492° 40′	709° 40′	$-146°$	563° 40′	563° 40′

Plotted in polar co-ordinates, the left-hand side of eqn. (14) gives a spiral $r = \alpha$, while the right-hand side is represented by n circles of diameters V_1V_0/K_1X_1, V_2V_0/K_2X_2 . . . V_nV_0/K_nX_n. The spiral may for convenience be plotted on a transparent sheet which is free to rotate about the pole and is provided with a protractor scale.

To solve the problem assume that $\theta_1 = \theta_2 = \ldots = \theta_n = \theta_a$ (say) and obtain as a first approximation, from eqn. (16),

$$\cot\theta_a = \frac{X_L + Z_L^2\Sigma\frac{1}{X}}{R_L}$$

and from eqn. (15)

$$V_a = \left(\frac{Z_L^2}{R_L}\sin\theta_a\right)\Sigma\frac{V}{X}$$

where V_a is the first approximation to the load voltage. Taking this value of V_a draw the circles 1, 2, . . . , n of diameters V_1V_a/K_1X_1, . . . V_nV_a/K_nX_n (see Fig. 11), with a common pole

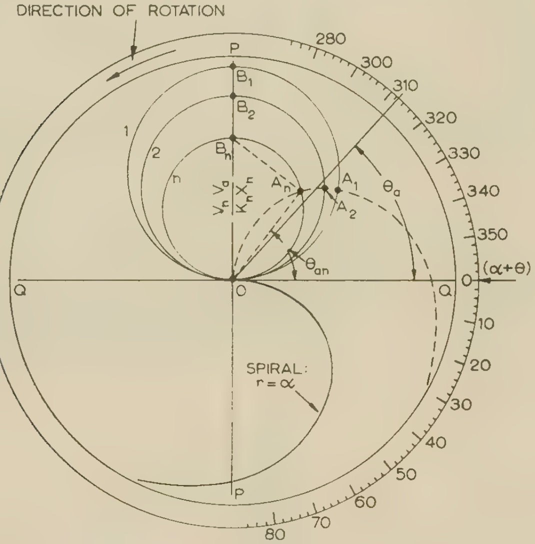


Fig. 11.—Graphical solution of the n-machine case.

at O, and superpose on the drawing the transparent sheet in such a way that the pole of the spiral is pivoted at O. Starting from the zero position of the spiral, shown by the full line $r = \alpha$ in Fig. 11, the transparent sheet is now rotated until an angle has been swept out, on the protractor scale, equal to $(\theta_a + \alpha_{1a})$, where $\alpha_{1a} = (V_1V_a/K_1X_1)\sin\theta_a$. The spiral will be intersected by the circles at the points A_1, A_2, . . . A_n which individually satisfy the equations:

$$\alpha_{1a} = OA_1 = \frac{V_1V_a}{K_1X_1}\sin\theta_{1a}$$

$$\alpha_{2a} = OA_2 = \frac{V_2V_a}{K_2X_2}\sin\theta_{2a}$$

$$\cdots\cdots$$

$$\alpha_{na} = OA_n = \frac{V_nV_a}{K_nX_n}\sin\theta_{na}$$

in which $\theta_{1a} = \angle A_1OQ$, $\theta_{2a} = \angle A_2OQ$, . . . $\theta_{na} = \angle A_nOQ$ (showing that the θ's will not in general be equal as assumed in the first approximations).

We now have to satisfy eqn. (16). This is done by rotating the spiral until points of intersection A_1', A_2', . . . A_n' are found such that

$$\frac{K_1A_1'B_1 + K_2A_2'B_2 + \ldots + K_nA_n'B_n}{K_1OA_1' + K_2OA_2' + \ldots + K_nA_n'} = \frac{X_L + Z_L^2\Sigma\frac{1}{X}}{R_L}$$

When this condition has been satisfied, $\theta_1 = \angle A_1'OQ$, $\theta_2 = \angle A_2'OQ$, . . . $\theta_n = \angle A_n'OQ$; while $\theta_1 + \alpha_1 = \theta_2 + \alpha_2 = \ldots = \theta_n + \alpha_n$ is equal to the angle swept out on the protractor scale and which satisfies eqn. (17).

The load voltage, V_b, can now be calculated from eqn. (15) and the result compared with the assumed value V_a; if there is a serious discrepancy, the circles 1, 2, . . . n must be redrawn with the diameters V_1V_b/K_1X_1, . . . V_nV_b/K_1X_1 and the process of satisfying eqns. (14) and (16) repeated. In general, it is found that only one or two recalculations are necessary to ensure sufficient accuracy, and the process of solution, though apparently laborious, is found in practice to give results of sufficient accuracy quite quickly (see Section 4.1).

Here again it will be seen that the division of the total load between the generators can occur in a number of different ways, since the spiral may cut the machine circles in a number of points; any set of these points which will fulfil eqns. (15)–(17) will represent a possible mode of operation. Thus we may have a more or less equal load division with all machines operating at comparatively small load angles, or the system may so arrange itself that one or more machines work with large load angles and the remainder with very small ones. For any mode, however, the approximation $\theta_1 = \theta_2 = \ldots = \theta_n = \theta_a$ gives a good guide, since the trigonometrical functions repeat themselves every 360°.

If the reference vectors are shifted from the absolute by the angles α_{01}, α_{02}, . . . α_{0n}, condition (14) will become

$$\left.\begin{aligned} \alpha_1 &= \alpha_{01} + \frac{V_1V_0}{K_1X_1}\sin\theta_1 \\ \alpha_2 &= \alpha_{02} + \frac{V_2V_0}{K_2X_2}\sin\theta_2 \\ &\cdots\cdots \\ \alpha_n &= \alpha_{0n} + \frac{V_nV_0}{K_nX_n}\sin\theta_n \end{aligned}\right\} \quad . \quad . \quad . \quad . \quad (18)$$

while eqn. (16) will remain unaltered.

Plotted in polar co-ordinates, the left-hand side of eqn. (18) remains the spiral $r = \alpha$, while the right-hand side is represented in general by n limacons. The procedure explained before can be applied to satisfy eqn. (16).

It may be of interest to apply the polar co-ordinates to the case where the machines are controlled by centrifugal governors. Assuming equal no-load speeds for all prime movers, the equations which must be satisfied are

$$\frac{f_0 - f}{V_0} = \frac{V_1}{C_1X_1}\sin\theta_1 = \frac{V_2}{C_2X_2}\sin\theta_2 = \ldots = \frac{V_n}{C_nX_n}\sin\theta_n \quad (19)$$

$$\frac{\Sigma\frac{V}{X}\cos\theta}{\Sigma\frac{V}{X}\sin\theta} = \frac{X_L + Z_L^2\Sigma\frac{1}{X}}{R_L} \quad . \quad . \quad . \quad . \quad . \quad (20)$$

$$\Sigma\frac{V}{X}\sin\theta = \frac{R_L}{Z_L^2}V_0 \quad . \quad . \quad . \quad . \quad . \quad . \quad (21)$$

Plotted in polar co-ordinates, the left-hand side of eqn. (19) gives a circle of radius $r = (f_0 - f)/V_0$ and centre at O, while the right-hand side is represented by n circles of diameters

$/C_1X_1, \ldots V_n/C_nX_n$. To solve the problem a circle, with O centre, is chosen such that eqn. (20) is satisfied; a straight line th an angle θ_a to the horizontal will help to indicate the proximate radius of the circle. The radius of the circle defines $-f/V_0$, and by the use of eqn. (21), V_0 and f can be calculated mediately (see Section 4.2).

4.1) Example—Three Machines Controlled by Displacement Governors

Three sets are connected in parallel to supply a dead load of istance $R_L = 3{\cdot}2$ ohms in series with a reactance $X_L =$ 4 ohms. The particulars of the sets are:

	Set 1	Set 2	Set 3
V, volts/phase	1 500	800	1 000
X, ohms/phase ..	15	10	12
K, kW/rad	10	5	7

ference vectors are not shifted from the absolute, i.e.

$$\alpha_{01} = \alpha_{02} = \alpha_{03} = 0$$

om which

$$\Sigma\frac{1}{X} = 0{\cdot}2501 \quad \Sigma\frac{V}{X} = 263{\cdot}4 \quad \frac{Z_L^2}{R_L} = \frac{16}{3{\cdot}2}$$

e condition

$$\frac{\Sigma\frac{V}{X}\cos\theta}{\Sigma\frac{V}{X}\sin\theta} = \frac{X_L + Z_L^2\Sigma\frac{1}{X}}{R_L} = 2$$

ist be satisfied.

Now assume $\theta_1 = \theta_2 = \theta_3 = \theta_a$ (say); then

$$\cot\theta_a = 2 \quad \theta_a = 26^\circ\,25' \quad \sin\theta_a = 0{\cdot}447$$

ence

$$V_a = \frac{Z_L^2}{R_L}\sin\theta_a\Sigma\frac{V}{X} = \frac{16}{3{\cdot}2} \times 0{\cdot}447 \times 263{\cdot}4 \text{ volts} = 588 \text{ volts}$$

$$\alpha_{1a} = \frac{V_1V_a}{K_1X_1}\sin\theta_a = \frac{1\,500 \times 588}{10\,000 \times 15} \times 0{\cdot}447 \text{ rad}$$

$$= 2{\cdot}628 \text{ rad} = 150^\circ\,30'$$

$$\theta_a + \alpha_{1a} = 176^\circ\,55'$$

d the circle diameters VV_a/KX are 337°, 540° and 400°.

Now rotate the spiral through the angle $\theta_a + \alpha_{1a}$, corresponding to the first approximation, and by a further increment rotation either positive or negative obtain the points of ersection between spiral and circles which give:

	$\frac{VV_0}{KX}\sin\theta$ deg	$\frac{VV_0}{KX}\cos\theta$ deg	$\frac{VV_0}{X}\sin\theta$ watts	$\frac{VV_0}{X}\cos\theta$ VAr
Set 1 ..	177·6	292	31 000	51 000
Set 2 ..	189·2	504	16 500	44 000
Set 3 ..	182·4	364	22 300	44 500

ence $\Sigma\frac{VV_0}{X}\sin\theta = 69\,800 \quad \Sigma\frac{VV_0}{X}\cos\theta = 139\,500$

ich yields the required ratio

$$\frac{\Sigma\frac{V}{X}\cos\theta}{\Sigma\frac{V}{X}\sin\theta} = \frac{139\,500}{69\,800} = 2$$

Having defined the points of intersection, we obtain

$$\alpha + \theta = 210^\circ \text{ (same for all sets)}$$
$$\theta_1 = 31^\circ \qquad \alpha_1 = 179^\circ$$
$$\theta_2 = 20^\circ\,30' \quad \alpha_2 = 189^\circ\,30'$$
$$\theta_3 = 26^\circ \qquad \alpha_3 = 184^\circ$$

and

$$V_b^2 = \frac{Z_L^2}{R_L}\Sigma\frac{VV_b}{X}\sin\theta = \frac{16}{3{\cdot}2} \times 69\,800 \text{ (volts)}^2\text{: } V_b = 591 \text{ volts}$$

It is seen that the difference between V_b and V_a is 0·5%. A closer approximation could be obtained, if required, by replotting the circles to diameters corresponding to V_b (591 volts) and repeating the process described.

Multiple solutions exist; for instance, steady-state operation can also occur when

(a) $\theta_1 = 71^\circ \quad \alpha_1 = 316^\circ \quad P_1 = 55{\cdot}1\,\text{kW}$
$\theta_2 = 369^\circ \quad \alpha_2 = 18^\circ \quad P_2 = 1{\cdot}57\,\text{kW}$
$\theta_3 = 371^\circ \quad \alpha_3 = 16^\circ \quad P_3 = 1{\cdot}95\,\text{kW}$

(b) $\theta_1 = 377^\circ \quad \alpha_1 = 98^\circ \quad P_1 = 17{\cdot}1\,\text{kW}$
$\theta_2 = 51^\circ \quad \alpha_2 = 424^\circ \quad P_2 = 37\,\text{kW}$
$\theta_3 = 374^\circ \quad \alpha_3 = 101^\circ \quad P_3 = 12{\cdot}6\,\text{kW}$

(c) $\theta_1 = 372^\circ \quad \alpha_1 = 60^\circ \quad P_1 = 10{\cdot}48\,\text{kW}$
$\theta_2 = 368^\circ \quad \alpha_2 = 64^\circ \quad P_2 = 5{\cdot}59\,\text{kW}$
$\theta_3 = 67^\circ \quad \alpha_3 = 365^\circ \quad P_3 = 44{\cdot}5\,\text{kW}$

The value of θ at which steady-state operation for a given set just ceases to be possible (the stability limit of the set) can be found by rotating the spiral through an angle θ_m, say, until it just touches the machine circle. Stable operating points must therefore be confined to that part of the circle included between $\theta = 0$ and $\theta = \theta_m$. For the example taken above

	Set 1	Set 2	Set 3
$\theta_m =$	100°	96°	98°

Fig. 12 shows the spiral and circles set up for the solution of this problem. The heavy curves are the spirals $r = a\alpha$, where

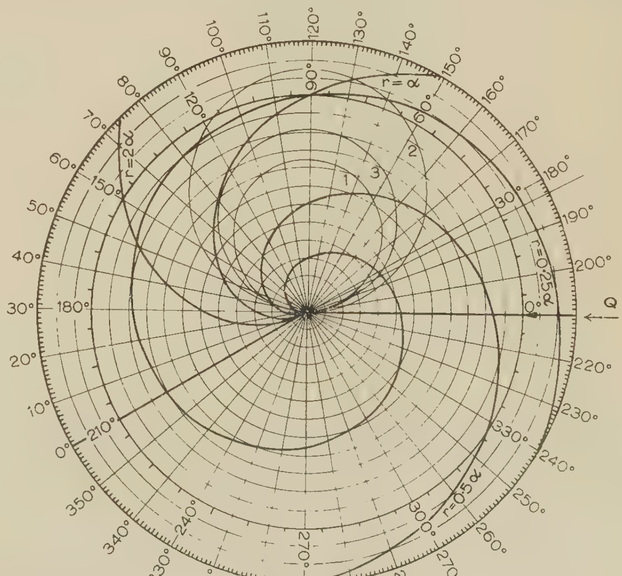


Fig. 12.—The calculating board used for solving a 3-machine problem.

a is a scale factor, plotted on a transparent polar chart for $a = 2$, 1, 0·5 and 0·25. The spiral was drawn with the radius plotted to the four scales, so that the same polar chart could be used for a number of problems in each of which the machine circles would be plotted to a convenient scale. In any particular solution the spiral plotted to the same scale as the circles can be picked out and used for that solution, the one used with this problem being $r = 0{\cdot}25\alpha$. The spirals rotate with the outside protractor scale against the datum OQ and the angle $\theta + \alpha$ appears on the outside scale. The machine circles 1, 2 and 3 are plotted on drawing paper and the polar chart superimposed upon them so that the poles coincide. It was found convenient, since it gives θ directly, to use a second protractor fixed with regard to the circles. This can be seen as the inner divided circle with its zero at Q.

(4.2) Example: Three Machines Controlled by Centrifugal Governors

Three sets are connected in parallel to supply a dead load of resistance $R_L = 3{\cdot}2$ ohms in series with a reactance $X_L = 2{\cdot}4$ ohms (at 50 c/s). The particulars of the sets are given in Table 4.

Table 4

Set	V (at 50 c/s)	X (at 50 c/s)	C	f_0	$\frac{V}{CX}$	$\frac{f_0 - f}{V_0} = \frac{V}{CX}\sin\theta$	$\frac{V}{X}\sin\theta$	$\frac{V}{CX}\cos\theta$	$\frac{V}{X}\cos\theta$
	volts/phase	ohms/phase	kW per c/s	c/s			amp		amp
1	1 500	15	15	52	0·006 67	0·003 6	54	0·005 67	85
2	800	10	8	52	0·010 65	0·003 6	27	0·01	75
3	1 000	12	10	52	0·008 33	0·003 6	36	0·007 4	74

whence

$$\Sigma\frac{V}{X}\sin\theta = 117 \quad \Sigma\frac{V}{X}\cos\theta = 234$$

and therefore

$$\frac{\Sigma\frac{V}{X}\cos\theta}{\Sigma\frac{V}{X}\sin\theta} = \frac{234}{117} = 2$$

$$\theta_1 = 31^\circ\,30' \quad \theta_2 = 19^\circ \quad \theta_3 = 25^\circ$$

$$V_o = \frac{16}{3{\cdot}2} \times 117 \text{ volts} = 585 \text{ volts}$$

$$f_0 - f = 2{\cdot}11\,\text{c/s} \quad f = 49{\cdot}89\,\text{c/s}$$

$$P_1 = 54 \times 585 \text{ watts} = 31{\cdot}6\,\text{kW}$$

$$P_2 = 27 \times 585 \text{ watts} = 15{\cdot}8\,\text{kW}$$

$$P_3 = 36 \times 585 \text{ watts} = 21{\cdot}1\,\text{kW}$$

(5) CONCLUSIONS

In the foregoing discussion we have tried to treat the theory of displacement governing so far as it applies to steady-state operation and little has been said about the implications of this type of control in the practical case.

Displacement governing has certain desirable features:

(a) The effective synchronizing stiffness of each turbo-alternator set is increased, owing to characteristics of the governor control, and as a result the load-angle range for stable operation is extended. This increased stiffness may well be helpful when sets have to operate with reduced excitation, e.g. on a leading power factor, and the extension of the range for steady-state operation will also imply an increased stability under transient conditions.

(b) A network supplied by a number of sets controlled by displacement governors will operate, in the steady state, at a frequency which is strictly constant and independent of load and which is defined by the angular velocity of the standard vector. The network frequency is anchored to the standard frequency; there can be no stable operation at frequencies other than this. It follows that two discrete networks controlled from the same standard vector will always be in synchronism, though not necessarily in phase, in the steady state. If the networks are to be interconnected electrically they may be brought into phase by adjustment of the angular shift, α_0, of either network, and once interconnection has been established the apportioning of load between them may be controlled by adjusting the relative angular shift.

Certain difficulties would be encountered in applying displacement governing to a large network. Perhaps the most serious would be that arising on account of the multiple solutions of the load equations which have been shown to exist. These solutions imply that there are a number of modes in which the total load may apportion itself between the sets which supply the network. Suppose that a network, operating in the steady state on a given load and with a given distribution of load between its sets, is subjected to a sudden disturbance which, after being applied for a given time, is subsequently removed. If the disturbance is large it may well be found that the final load distribution differs very considerably from that which obtained before the advent of the disturbance, though the total load may be little affected. The mode of load distribution adopted by the network will depend on the magnitude and duration of the disturbance and upon the dynamical and transient constants of the sets. It can be predicted, but treatment of the problem would be out of place here.

It must be remembered too that with displacement governing there is a relationship, even if losses are neglected, between the excitation carried by a given machine and the load which it will deliver to the network, an increased field excitation being in general associated with an increase in electrical output.

Immediate practical problems will arise in bringing the standard frequency to each generating point and in providing a valve linkage which, operating on the prime movers, will ensure that their shaft torque shall at all times be a linear function of the angular displacement between the machine and reference vector. The first might be solved by transmitting the standard frequency or a multiple of it from one standard source to all the sets, or, alternatively, local sources of standard frequency might be used and arrangements made to maintain these in exact phase relation with each other. The single source would have obvious advantages where large networks remote from each other were to be operated in parallel. It is possible that either pulse or carrier techniques could be applied. The control of prime-mover torque to hold it as a linear function of an angular displacement introduces problems which we hope to treat in a

per on the transient performance of displacement governors, t a simple example may be included here to indicate the speed response that would be required.

Suppose that the armature of a set, initially loaded, is sud- ıly disconnected from the network. When disconnected the will move under the control of its governor according to the ıation

$$K\alpha + \frac{2HP_f}{\omega}\frac{d^2\alpha}{dt^2} = 0$$

simplicity the angular shift α_0 is assumed to be zero.

The equation implies a simple harmonic motion having a riodic time $T = 2\pi\sqrt{(2P_fH/K\omega)}$. The equation does not ld for negative values of α, since the turbine cannot provide negative (motoring) torque, but may be regarded as describing motion during the first quarter period, which will be the time quired to reduce α from its maximum to zero. If this time is we have

$$t_0 = \frac{T}{4} = \frac{\pi}{2}\sqrt{\frac{2P_fH}{K\omega}}$$

ıen α is zero the turbine driving torque, $K\alpha$, must be zero d t_0 is therefore the time available for bringing it to zero.

Suppose that a set having an inertia constant of 6 kW-sec kilowatt operates at full load with a governor displacement gle of 2π radians giving

$$2\pi K = P_f \quad K = \frac{P_f}{2\pi}$$

ow let the set be disconnected suddenly from the network; have

$$t_0 = \frac{\pi}{2}\sqrt{\frac{24\pi P_f}{P_f\omega}}$$

$$= 0{\cdot}77\,\text{sec}$$

$\omega = 100\pi$, as the time during which the turbine torque must l from its full-load value to zero.

The time t_0 may of course be increased by increasing the inertia nstant of the set or by reducing the governor gain, of which e second would appear to be the more practical expedient; but must be reduced to one-quarter of its original value in order double t_0. An estimate may also be made of the speed over- oot that would be caused by the removal of the electrical load. e motion during the first quarter cycle of swing may be itten

$$\alpha = \hat{\alpha}\sin\Omega t$$

ıere $\hat{\alpha}$ is the maximum angular deflection and $\Omega = \sqrt{(K\omega/2P_fH)}$. From this we have the maximum swinging locity

$$\left(\frac{d\alpha}{dt}\right)_{max} = \hat{\alpha}\Omega$$

ıich will occur after time t_0, i.e. when $\alpha = 0$. In our example $= 2\pi$, $\Omega = 2{\cdot}04$ and therefore $(d\alpha/dt)_{max} = 2\pi \times 2{\cdot}04 =$ $\cdot 8$ rad/sec, or a maximum speed increase of

$$\frac{12{\cdot}8}{100\pi} = 4{\cdot}05\%$$

is speed increase is also a function of the governor gain and e inertia constant, but it should be noticed that if the gain is duced to one-quarter of its original value the speed increase ll be doubled.

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(7) APPENDICES

(7.1) Rigorous Solution for the Case of Two Symmetrical Machines

For the system shown in Fig. 13,

$$P_{e1} = \frac{V_1^2}{Z_{11}}\cos\phi_{11} - \frac{V_1V_2}{Z_{12}}\cos(\theta_{12} + \phi_{12}) \quad . \quad (22)$$

$$P_{e2} = \frac{V_2^2}{Z_{22}}\cos\phi_{22} - \frac{V_1V_2}{Z_{12}}\cos(\theta_{21} + \phi_{12}) \quad . \quad (23)$$

where

$$Z_{11}\angle\phi_{11} = \dot{Z}_1 + \frac{\dot{Z}_2\dot{Z}_L}{\dot{Z}_2 + \dot{Z}_L}$$

$$Z_{22}\angle\phi_{22} = \dot{Z}_2 + \frac{\dot{Z}_1\dot{Z}_L}{\dot{Z}_1 + \dot{Z}_L}$$

$$Z_{12}\angle\phi_{12} = \dot{Z}_1 + \dot{Z}_2 + \frac{\dot{Z}_1\dot{Z}_2}{\dot{Z}_L}$$

$$\theta_{12} = \theta_1 - \theta_2 \quad \theta_{21} = \theta_2 - \theta_1$$

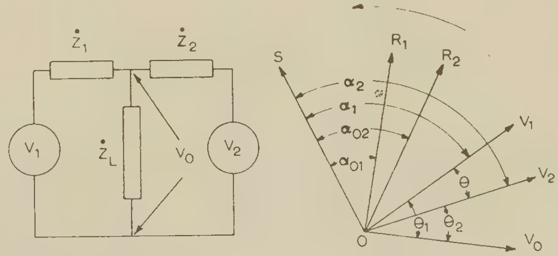

Fig. 13.—Two machines working in parallel and supplying a dead load.

Also
$$P_{i1} = K_1(\alpha_1 - \alpha_{01}) \quad . \quad . \quad . \quad . \quad . \quad (24)$$
$$P_{i2} = K_2(\alpha_2 - \alpha_{02}) \quad . \quad . \quad . \quad . \quad . \quad (25)$$

If turbine losses are neglected, we may combine eqns. (22) and (24) and eqns. (23) and (25). Thus

$$K_1(\alpha_1 - \alpha_{01}) = \frac{V_1^2}{Z_{11}}\cos\phi_{11} - \frac{V_1V_2}{Z_{12}}\cos(\theta_{12} + \phi_{12})$$
$$K_2(\alpha_2 - \alpha_{02}) = \frac{V_2^2}{Z_{22}}\cos\phi_{22} - \frac{V_1V_2}{Z_{12}}\cos(\theta_{21} + \phi_{12})$$

Dividing the first equation by K_1 and the second by K_2 and subtracting,

$$(\alpha_1 - \alpha_2) + (\alpha_{02} - \alpha_{01}) = \left(\frac{V_1^2}{K_1Z_{11}}\cos\phi_{11} - \frac{V_2^2}{K_2Z_{22}}\cos\phi_{22}\right) - \frac{V_1V_2}{Z_{12}}\left[\frac{1}{K_1}\cos(\theta_{12} + \phi_{12}) - \frac{1}{K_2}\cos(\theta_{21} + \phi_{12})\right] \quad . \quad . \quad . \quad . \quad (26)$$

From the vector diagram, $\alpha_1 + \theta_1 = \alpha_2 + \theta_2$, i.e. $\alpha_1 - \alpha_2 = \theta_2 - \theta_1$. Substituting in eqn. (26) and letting $\theta = \theta_1 - \theta_2$,

$$-\theta + (\alpha_{02} - \alpha_{01}) = A + BC\sin(\theta - \lambda) \quad . \quad (27)$$

where

$$\left.\begin{aligned} A &= \frac{V_1^2}{K_1Z_{11}}\cos\phi_{11} - \frac{V_2^2}{K_2Z_{22}}\cos\phi_{22} \\ B &= \frac{V_1V_2}{Z_{12}} > 0 \\ C^2 &= \left(\frac{1}{K_1} + \frac{1}{K_2}\right)^2 - \frac{4}{K_1K_2}\cos^2\phi_{12} \quad C > 0 \\ \tan\lambda &= \frac{K_2 - K_1}{K_2 + K_1}\cot\phi_{12} \quad 90^\circ \geqslant \lambda \geqslant -90^\circ \end{aligned}\right\} \quad . \quad (28)$$

Let $\theta' = \theta - \lambda$ and $\alpha_{eq} = (\alpha_{02} - \alpha_{01}) - (A + \lambda)$:

then
$$\frac{\alpha_{eq} - \theta'}{BC} = \sin\theta' \quad . \quad . \quad . \quad . \quad . \quad (29)$$

Fig. 14 shows the graphical solution of eqn. (29). The form in which this equation is written allows a single sine curve, of

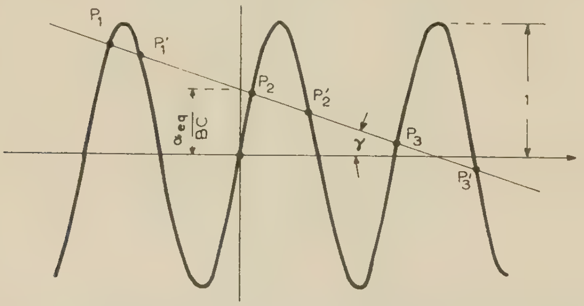

Fig. 14.—Graphical solution of eqn. (29).
$\tan\gamma = 1/BC$

unit peak value, to be used and all variables are allowed for by drawing a straight line of appropriate slope and intercept. The relation between α_{eq} and θ' is shown in Fig. 15 for different values of $1/BC$ and could be used, without returning to the graphical solution, to determine the angular separation between the rotors for any given α_{eq} and $1/BC$ for the case of no pole slipping.

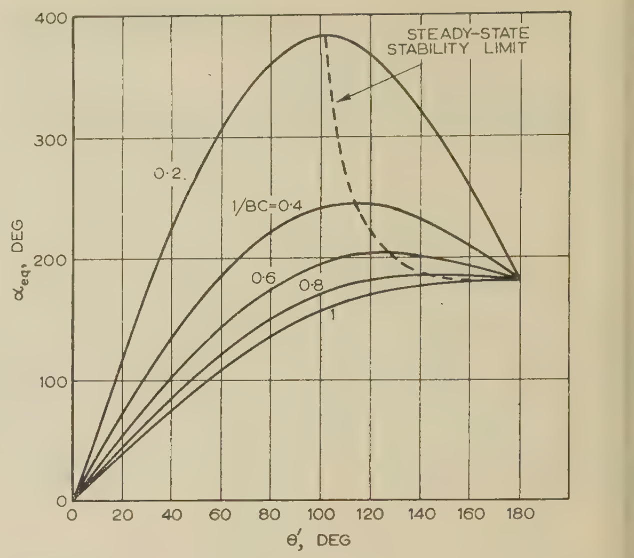

Fig. 15.—Relation between α_{eq} and θ' for different values of $1/BC$ from eqn. (29).

(7.2) Steady-State Stability of the Two-Machine Case

The concept of the sign of the synchronizing power coefficient has been used as a method for testing for steady-state stability[7-10] for the case of machines controlled by centrifugal governors. The condition of stability in this case is simply that the synchronizing power coefficient shall be positive at the given operating point. This criterion is equivalent to giving the rotor a small additional angular displacement and then releasing it. If the rotor returns to its original displacement with respect to the other machines, the system is stable. In general, stability exists if a positive increment in the angular displacement of one machine relative to the others brings about a greater change in its electrical power output than the change that may result in its mechanical power input.

For the 2-machine system of Fig. 13 the condition for stability is therefore

$$\left.\begin{aligned} &\text{for machine 1: } \Delta P_{e1} > \Delta P_{i1} \\ &\text{for machine 2: } \Delta P_{e2} > \Delta P_{i2} \end{aligned}\right\} \Delta\theta > 0$$

$$\left.\begin{aligned} &\text{Thus} \quad \frac{V_1V_2}{Z_{12}}\sin(\theta_{12} + \phi_{12})\Delta\theta_{12} > K_1\Delta\alpha_1 \\ &\text{and} \quad \frac{V_1V_2}{Z_{12}}\sin(\theta_{21} + \phi_{12})\Delta\theta_{21} > K_2\Delta\alpha_2 \end{aligned}\right\} \quad . \quad . \quad (30)$$

But $\quad \Delta\theta_{12} = \Delta\alpha_2 - \Delta\alpha_1$ and $\Delta\theta_{21} = \Delta\alpha_1 - \Delta\alpha_2$:

Therefore, substituting in eqn. (30) and rearranging,

$$\frac{1}{K_1}\sin(\theta + \phi_{12}) > \frac{Z_{12}}{V_1V_2}\frac{\Delta\alpha_1}{\Delta\alpha_2 - \Delta\alpha_1}$$
$$-\frac{1}{K_2}\sin(\theta - \phi_{12}) > \frac{Z_{12}}{V_1V_2}\frac{\Delta\alpha_2}{\Delta\alpha_1 - \Delta\alpha_2}$$

Adding,

$$\frac{1}{K_1}\sin(\theta + \phi_{12}) - \frac{1}{K_2}\sin(\theta - \phi_{12}) > -\frac{Z_{12}}{V_1V_2}$$

i.e.
$$\cos(\theta - \lambda) > -\frac{1}{BC} \quad . \quad . \quad . \quad . \quad (31)$$

stable operation, where B, C and λ are as defined by eqn. (28). fferentiating eqn. (27) with respect to θ,

$$\cos(\theta - \lambda) = -\frac{1}{BC}$$

s $(\theta - \lambda)$ is the slope of the sine curve in Fig. 14, while $-1/BC$ the slope of the straight line, and from condition (31), if the mer is greater than the latter at any intersection point, bility exists.

Although the sine curve and the straight line have no simple ysical interpretation, they can be used to indicate the stable ints of operation. The sine curve could therefore be looked on as being to some extent analogous to an output power rve and the straight line to an input line.

(7.3) Approximate Treatment of the Multi-Machine Case

An approximate treatment of the 2-machine system has eady been given by Broadbent.[3] Using his nomenclature, this n be extended to the multi-machine case. Fig. 16 shows the

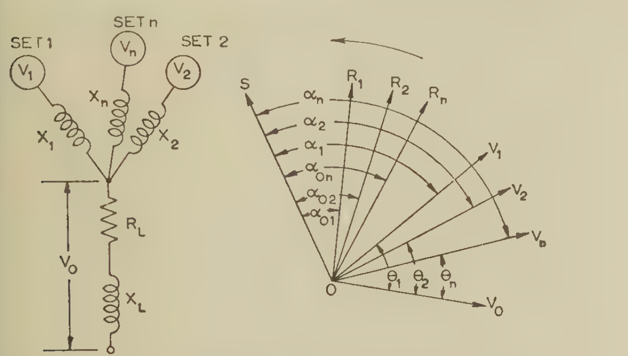

Fig. 16.—A group of machines supplying a dead load and the corresponding vector diagram.

uivalent circuit of a group of alternators and the corresponding ctor diagram. Each machine is assumed to be controlled by displacement governor. The e.m.f.'s represented by vectors V_1, OV_2, . . . OV_n, lag in relation to the standard vector OS, does the common terminal voltage OV_0. If the machines assumed to have large synchronizing powers, i.e. low synronous reactances and high air-gap fluxes, the terminal voltage n be considered constant. Consequently, for constant excitan currents and small power angles, the synchronizing power efficients $P_{sn} = dP_e/d\theta$ are considered constant. From g. 16,

$$\alpha_1 + \theta_1 = \alpha_2 + \theta_2 = \ldots = \alpha_n + \theta_n \qquad (32)$$

ie output powers are given by

$$P_1 = P_{s1}\theta_1,\ P_2 = P_{s2}\theta_2, \ldots P_n = P_{sn}\theta_n \qquad (33)$$

ile the input powers are given by

$$P_1 = K_1(\alpha_1 - \alpha_{01}),\ P_2 = K_2(\alpha_2 - \alpha_{02}), \ldots P_n = K_n(\alpha_n - \alpha_{0n}) \qquad (34)$$

bstitution of eqns. (33) and (34) in (32) gives

$$\left(\frac{P_1}{K_1} + \alpha_{01}\right) + \frac{P_1}{P_{s1}} = \left(\frac{P_2}{K_2} + \alpha_{02}\right) + \frac{P_2}{P_{s2}} = \ldots = \left(\frac{P_n}{K_n} + \alpha_{0n}\right) + \frac{P_n}{P_{sn}}$$

and

$$\alpha_{01} + \left(\frac{1}{K_1} + \frac{1}{P_{s1}}\right)P_1 = \alpha_{02} + \left(\frac{1}{K_2} + \frac{1}{P_{s2}}\right)P_2 = \ldots = \alpha_{0n} + \left(\frac{1}{K_n} + \frac{1}{P_{sn}}\right)P_n \qquad (35)$$

Given α_{0n}, P_{sn} and K_n, the load on each machine can be determined for any total load.

If all the reference vectors are given the same angular shift from the standard, i.e. $\alpha_{01} = \alpha_{02} = \ldots = \alpha_{0n}$ eqn. (35) will reduce to

$$\left(\frac{1}{K_1} + \frac{1}{P_{s1}}\right)P_1 = \left(\frac{1}{K_2} + \frac{1}{P_{s2}}\right)P_2 = \ldots = \left(\frac{1}{K_n} + \frac{1}{P_{sn}}\right)P_n \qquad (36)$$

and

$$P_n/\Sigma P = \frac{1}{\frac{1}{K_n} + \frac{1}{P_{sn}}} \Big/ \Sigma \frac{1}{\frac{1}{K} + \frac{1}{P_s}} \qquad (37)$$

(7.4) Graphical Solution for n Symmetrical Machines

A more exact solution which does not involve the assumption of constant synchronizing power coefficients may be obtained. A graphical solution for n machines is possible if the machines are assumed to be symmetrical and their armature resistances are neglected.

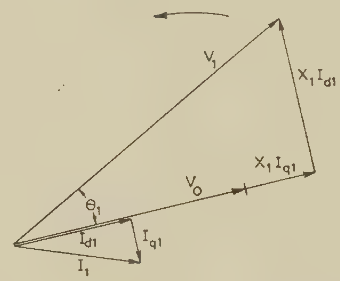

Fig. 17.—Vector diagram of a single machine.

Fig. 17 shows the vector diagram of a single machine of the system given in Fig. 16.

For machine 1,

$$V_1 \cos\theta_1 - V_0 = X_1 I_{q1}$$

thus

$$I_{q1} = \frac{V_1}{X_1}\cos\theta_1 - \frac{V_0}{X_1}$$

Similarly, for machine 2,

$$I_{q2} = \frac{V_2}{X_2}\cos\theta_2 - \frac{V_0}{X_2}$$

and for machine n,

$$I_{qn} = \frac{V_n}{X_n}\cos\theta_n - \frac{V_0}{X_n}$$

Adding

$$\Sigma I_q = \Sigma\frac{V}{X}\cos\theta - V_0\Sigma\frac{1}{X}$$

ΣI_q is the total reactive current flowing through the load and is equal to $X_L V_0/Z_L^2$. Therefore

$$\frac{X_L}{Z_L^2}V_0 = \Sigma\frac{V}{X}\cos\theta - V_0\Sigma\frac{1}{X}$$

and $$\Sigma\frac{V}{X}\cos\theta = \left(\frac{X_L}{Z_L^2} + \Sigma\frac{1}{X}\right)V_0 \quad . \quad . \quad . \quad (38)$$

Also $$I_{d1} = \frac{V_1}{X_1}\sin\theta_1, I_{d2} = \frac{V_2}{X_2}\sin\theta_2, \ldots I_{dn} = \frac{V_n}{X}\sin\theta_n$$

Adding $$\Sigma I_d = \Sigma\frac{V}{X}\sin\theta$$

ΣI_d is the total active current flowing through the load and is equal to $R_L V_0/Z_L^2$.

Therefore

$$\Sigma\frac{V}{X}\sin\theta = \frac{R_L}{Z_L^2}V_0 \quad . \quad . \quad . \quad . \quad . \quad (39)$$

Dividing eqn. (38) by eqn. (39),

$$\frac{\Sigma\frac{V}{X}\cos\theta}{\Sigma\frac{V}{X}\sin\theta} = \frac{X_L + Z_L^2\Sigma\frac{1}{X}}{R_L} \quad . \quad . \quad . \quad (40)$$

which must be fulfilled.

DISCUSSION ON
'SUPPLY-VOLTAGE AND CURRENT VARIATIONS PRODUCED BY A 60-TON 3-PHASE ELECTRIC ARC FURNACE'*

Before the WESTERN CENTRE *at* CARDIFF 10*th November, the* SOUTH-WEST SCOTLAND SUB-CENTRE *at* GLASGOW 26*th November*, 1958, *and the* SOUTH MIDLAND SUPPLY AND UTILIZATION GROUP *at* BIRMINGHAM 9*th February*, 1959.

Mr. C. E. Dew (*at Cardiff*): On the financial side A. G. Robiette† indicated that, on the basis of tons per annum output, the capital cost of an electric arc furnace would only be about 60% more than that of an open-hearth furnace, and the running costs per ton of steel would be comparable between the two furnaces when due allowance is made for depreciation and interest charges at 12% per annum.

On the production side, the advantages in favour of the electric arc furnace would include (*a*) the facility for double slagging and the production of special steels, (*b*) the speed of charging (this being of particular importance for scrap having a low density/bulk ratio), and (*c*) the possibility of intermittent working during periods of low steel-output demand.

With an integrated iron and steel works, however, conversion of molten pig iron must be accommodated, and experience has indicated than an electric arc furnace is not satisfactory with a hot charge exceeding 30–35% of the total charge, although I believe that experience is now being gained in combining oxygen blowing, thus permitting hot charges of up to 50%.

Indeed Robiette implied that the pattern for an integrated works would be for the electric arc furnace to operate in conjunction with open-hearth furnaces and to fulfil the requirement of melting down scrap and thereby reduce tap-to-tap time on the open-hearth furnace.

The installation of large electric arc furnaces in the iron and steel industry is established practice in America, and we look forward to similar installations in this country. However, the load is considerable and requires, say, 500 kWh/ton for single slagging and over 600 kWh/ton for double slagging with the maximum demands as indicated by the authors. These loads cannot be added to an existing works system, and full liaison will be necessary with Area Boards from the inception of the project.

Reference is made in the paper to the short-circuit capacity required for a number of furnace transformers varying with the fourth root of the number of furnaces. This is indicated graphically in Fig. 1.

The paper makes a valuable contribution for consideration by the supply industry on what may be acceptable to them in terms of system disturbance. The next stage would seem to be to devise an economic formula and to agree with production personnel what would be acceptable in terms of unit size for any given installation.

It may well be established, for example, that 3–30-ton furnaces requiring a system short-circuit capacity of, say, 750 MVA would be more flexible from the production point of view than 2–60-ton furnaces requiring a short-circuit capacity of 1 000 MVA. The capital costs (considering switchgear, etc.) would also be no greater.

Mr. N. Care (*at Cardiff*): From the results of the tests carried out on the furnace installation, it would appear that little use can be made of the 11 kV system, which is interposed between the 66 kV Area network and the furnace itself. Is there any need for this 11 kV system, and, if not, could the furnace transformer and the Area Board transformer be combined into a much more economical arrangement?

I was surprised to find the wide tap range on the furnace transformer. Would a more economical arrangement be possible by the use of series reactors, which, to some extent, would be self-compensating in controlling the furnace current?

Was the provision of the tapped winding in any way influenced by the necessity to avoid voltage fluctuations on the incoming supply network? If the fault power available on the supply system was much greater than the example given in the paper and the supplies were taken from a 132 kV source, could not the tapped winding be dispensed with or simplified and the erratic variations in furnace current be tolerated, thus obtaining reduced operating costs?

Mr. F. J. Rennie (*at Glasgow*): In the Introduction the authors refer to a statement in papers published in the United States that 90% of people can distinguish a 1% voltage change in a tungsten lamp. Have the authors any information on the behaviour of television sets under the conditions of voltage variation discussed in the paper?

Figs. 7 and 8 indicate the considerable variations in phase current and the degree of unbalance encountered. Would it be possible to obtain a greater uniformity of arc currents by increasing the number of electrodes, say from three to six, which could be connected either 3-phase with two electrodes per phase or 6-phase? The initial cost of the furnace would certainly be increased, but this might be offset by improved performance.

The furnace was designed for 60 tons, but 'pours' of 70 tons

* ROBINSON, B. C., and WINDER, A. I.: Paper No. 2456 U, December, 1957 (see 105 A, p. 305).

† ROBIETTE, A. G.: *Iron and Coal Trades Review*, 27th November, 1953.

re easily obtainable. The oscillograms show that currents to 1·5 kA, or approximately twice full load on the 15 MVA /11 kV transformer, were recorded, but that, owing to the short ration of such currents, no thermal overload occurred. It refore appears than an even smaller furnace transformer uld have been satisfactory, and that the increased impedance the smaller unit would have reduced the voltage fluctuation the 66 kV network.

n Section 2.1 it is stated that 'Experience during the tests wed that the furnace operation was unstable for the first two four hours of each melt, and then fairly steady conditions e maintained during the remainder of the time'. Is it to be rred that, when most of the charge has melted, severe voltage iation is unlikely? In a recent lecture dealing with the design arc furnaces it was stated that voltage flicker could be caused the wandering of the arc over the surface of the hot metal, and t endeavours were being made to prevent this. In the same er it was stated that there appears to be little possibility of iding voltage variation by increasing the speed and response the electrode control gear, as this has already been tried hout success. Although the electricity supply industry is ling and anxious to supply consumers with all the power and rgy required, the use of apparatus which causes voltage iation in excess of what can reasonably be tolerated must be red. In the last resort the issue will be settled on the question economics. Furnace supplies could be obtained from the kV system, but the capital cost involved would probably prohibitive.

Mr. I. G. Edwards (*at Birmingham*): We are only too well re of the effects which the furnace current and voltage iations produce on a city distribution network. The intro-tion of furnaces of 60 tons and over has necessitated the ply being taken from the 132 kV system of the C.E.G.B., , even so, the voltage variations are such as to be noticeable. paper expresses in tangible form the magnitude of the effects ch arise when a very large furnace is connected to the supply. rom the paper it seems that the only stable opinion one can n is of the very instability of the factors which it sets out present. The currents and voltages vary within very wide its, and as larger furnaces are connected to the supply, the blems which arise will no doubt be accentuated.

Whilst the paper sets out, and succeeds admirably, in pre-ting the facts concerning voltage and current variation, one s that the authors should also have included information the methods of reducing the undesirable effects of these iations on the public supply system.

t is stated in the Summary that there is a temporary Grid ply point for this particular furnace. Are all the works stations fed from the same 132 kV circuit? I realize that furnace is supplied from its own substation, but nevertheless auxiliaries, together with the power and lighting for the nainder of the works, would be adversely affected by the ply variations which occur when the furnace is operating.

would like further clarification of the statement that 17% the total voltage variations occurring on the 132 kV system ur on the 66 kV network. Do the authors mean that only % are noticeable or that this is the percentage which passes lamped to the 66kV system? We are told that the greatest rational instability occurs when the charge is first introduced the furnace. Supply variations will therefore be widest ing this time. Are any special precautions taken in breaking or grading the charge?

Fig. 2 shows that the furnace transformer is quite a com-x arrangement in itself. Does this represent a special design these large furnaces? There appear to be two transformers olved. Is it possible to combine them into one? Would it not be possible to have the transformer connection made on the inter-star principle? It seems that, whilst the voltage distortion would be no greater than with the delta-star connection, the phase-current distribution might be somewhat improved (under, say, 2-phase arcing conditions), thus improving voltage regulation on the supply network.

Finally, in Section 4.1, I am interested in the method used to obtain the figure of $(4 \cdot 83 + 7 \cdot 2j)$ ohms for the impedance of the supply network. The application of Thévenin's theorem for this purpose involves the use of some numerical value for the current. As the furnace currents are so unstable, what value was chosen for the calculation?

When power-factor correction using static condensers has been applied to large furnaces, have any troubles been experienced from harmonic resonance?

Mr. R. Paterson (*at Birmingham*): Lighting flicker has been considerably reduced in Sheffield by uplifting the fault capacity of the system. Similarly, the moderate flicker that could be discerned by a trained eye in this district is now improved.

It is contemplated to reduce voltage variations by the connection of parallel reactors on electric-arc-furnace supply systems. Would the authors comment on the possibilities of economic improvement with such a scheme? So far, discussion has centred on the effects on the supply system of large electric arc furnaces.

Did the investigations reveal whether dangerously high voltages appeared on any part of the furnace transformer windings, and whether these high voltages, if any, could be suppressed?

Mr. H. M. Fricke (*at Birmingham*): I have knowledge of the installation of a 6 MVA bank of capacitors on a similar steel furnace in Glasgow. Could the authors comment on the question of harmonics which might appear to exist in the waveforms exhibited in the paper?

Dr. E. Friedlander (*at Birmingham*): If the voltage variations are between 75 and 140%, is it not likely that, in view of the unavoidable single-phasing of the furnace, these large variations will also cause increased losses in motors or similar disturbances, quite apart from the flicker of lights which is observed?

Would the authors not agree that shunt capacitors alone will increase the voltage fluctuation? They may help to absorb some of the harmonics, but without adequate precautions they may also amplify others. Both these consequences are due to shunt capacitors effectively shunting the supply impedance.

Mr. L. Goodall (*at Birmingham*): In the Introduction the authors refer to American practice based on $1\frac{3}{4}\%$ flicker voltage. Can we accept the figure of $1\frac{3}{4}\%$, or will that lead to numerous complaints?

Mr. E. C. Cooper (*at Birmingham*): The design of electric arc furnaces does not seem to have been improved during the years, and I would have thought that, in view of the considerable development which must have taken place in raising the capacity to 60 tons, there would have been some improvement in design to reduce the detrimental effects on the electricity supply caused by movement of the scrap as it melts down.

The supply engineer would welcome some guidance to assist in readily deciding what effect a particular furnace would have on the electricity supply under given conditions.

I note that flicker is noticeable only if its frequency is sufficiently low. Can we assume that the frequency of voltage variation caused by an arc furnace will be sufficiently low to produce a noticeable flicker, and that it cannot be altered by any modification to the design?

Messrs. B. C. Robinson and **A. I. Winder** (*in reply*): In reply to Mr. Care, no use was made of the 11 kV system in the installation tested except for metering of the power used. Provision was, however, made for connecting it to the works 11 kV supply

network, presumably as an auxiliary feed point should an emergency arise. In a second arc furnace installed since these tests the furnace transformer was connected directly to the 66 kV busbars.

Series reactors are used in some installations to limit the furnace load on short-circuit. In the installation described it was considered that the transformer and stray reactances were sufficient for this purpose. The objection to the use of reactors for controlling the load is that the power factor obtained would be too low. The tapping winding was used only for load control; it cannot be used to control voltage fluctuations in the supply network as these take place too rapidly for a tap changer to follow.

In reply to Mr. Edwards's questions, the works supplies were taken from the same 66 kV ring main as the furnace supply, although through substations an appreciable distance away. It is therefore unlikely that voltage variations greater than 10% of those measured on the furnace 11 kV system would reach the remainder of the works.

We have no direct information on the furnace transformer, but it would appear that it was constructed as two separate units to provide suitable operating conditions for the tapping-switch contacts. With regard to the use of an inter-star connection to reduce the voltage variations, we have already thought of this possibility but have had no opportunity to investigate it fully.

Mr. Rennie suggests that the voltage variations could be reduced by use of higher-impedance transformers. In fact, the reactance of the transformers does limit the disturbances considerably. During the tests the impedance of the substation transformer was about five times that of the 66 kV transmission lines to the substation. This accounts for the fact that only about 17% of the disturbance measured on the 11 kV busbars reaches the 66 kV network, as queried by Mr. Edwards. Mr. Edwards also asks how we calculated the impedance of the supply network without having a numerical value for the current. This was possible because the Electricity Board provided the various line and station impedances in ohms. When carrying out this calculation, all other loads were neglected, since their impedances were high compared with those of the lines and stations.

Mr. Rennie comments that a connection to the 275 kV system would be too expensive to make when supplying arc furnaces, but in the London discussion Mr. Sedden stated that this was, in fact, being considered.

In reply to Mr. Fricke and Dr. Friedlander, we have no more information on harmonics produced by the furnace than that given in the paper. The installation of capacitor power-factor correction should prove beneficial in reducing the voltage fluctuations.

Mr. Goodall wonders whether $1\frac{3}{4}$% flicker would be tolerable. Obviously this is a matter where individuals vary, but a lower figure would, of course, be desirable. So far as we can see, it is not possible to vary the flicker frequency, which is clearly visible.

Mr. Edwards asks whether any special precautions were taken in grading the scrap put into the furnace. This was beyond the range of our investigations, but from information gathered on the subject, we believe that it is possible to reduce the vigour of the furnace action, when melting down, by grading the scrap.

DISCUSSION ON
COMMUNICATION, INDICATION AND TELEMETERING FOR THE BRITISH GRID*

Before the North-Eastern Centre *at* Newcastle upon Tyne *24th November, the* South Midland Centre *at* Birmingham *1st December, the* South-East Scotland Sub-Centre *at* Edinburgh *16th December*, 1958, *the* North Midland Centre *at* Leeds *6th January, and the* North-Western Supply Group *at* Manchester *27th January*, 1959.

Mr. T. Sealy (*at Newcastle upon Tyne*): The aspect of Control Centre design which has received least attention in the past is the acoustical properties of the Control Room itself. Too often the ceiling, floor finishes, etc., are settled by the architect without the telecommunication engineer having any say in the matter. Inadequate use has been made of sound-absorbent materials, acoustical tiles, etc., in favour of hard plaster finishes, with resulting high noise levels. Telephone conversations are thereby made more difficult, with subsequent complaints, whilst, at quiet periods, complaints are received that certain instruments, clocks, etc., are said to be noisy. I would welcome the authors' views on this matter since it can have an appreciable effect on the efficiency of the system as a whole.

The synchronous-scan telemeter, as designed for the standardized system, has suffered from one bad design feature, namely the mixing of electronic and relay equipment on the same jack-in unit, all components being in the same can. The resultant heat produced has had adverse effects on telegraph relays and other components. What steps are being taken to overcome this problem in future designs?

The medium-speed intertripping system has the advantage that it can be directly superimposed on the standardized system. However, I understand that it has been largely replaced by one using three frequencies, but this has the disadvantage that it requires a separate line. Have practical difficulties been experienced with the former scheme or have other considerations led to this change?

Mr. F. H. Birch (*at Newcastle upon Tyne*): The standardized system was put into service in the Newcastle Grid Control Area at the end of November, 1957. Since then its performance has been good, as can be seen from Table A, which relates to that part of the Area east of the Pennines and to the eight-month period ending 31st October, 1958.

The overall performance is equivalent to rather less than one fault per day, and although the fault rate on lamps, valves and relays will probably increase, there is no reason to believe that the rates for the other components should alter materially. The average fault durations vary from 12 hours for a Post Office underground cable to a few minutes for a lamp fault at a Grid Control Centre when the maintenance staff are available to deal with it immediately.

The telephone system suffers from the limitation that, if a line or equipment is out of service, the caller receives the 'busy' tone instead of the 'line out of order' tone, as on the Post Office

* Gunning, P. F.: 'Standardization of Control Facilities for the British Grid: Communications, Indications and Telemetering', Paper No. 2626 S, May, 1958 (see 105 A, p. 554).
Burns, G. A., Fletcher, F., Chambers, C. H., and Gunning, P. F.: 'The Development of Communication, Indication and Telemetering Equipment for the British Grid', Paper No. 2627 S, May, 1958 (see 105 A, p. 565

Table A

Component	Approximate number in use	Number of faults
Post Office lines	34	31
Indicators and recorders	210	23
Relays: Post Office 3000 type	4600	19
Relays: Telegraph	180	15
Lamps	1050	14
Valves	1100	12
Cold-cathode tubes	300	0
Keys	1100	7
Dry batteries	20	6
Auxiliary switches	—	4
Other causes		
Work on equipment		12
Scrap wire		3
Miscellaneous		12
Unknown		45
	Total	203

national network. The caller will probably make several unsuccessful attempts to establish the call before realizing that the line is out of order.

Delayed automatic reclosing equipment is, in general, able to carry out switching operations more rapidly than an operator acting on instructions from the system control engineers. Where the switching operations necessary to restore the supply can be predetermined, it may be worth while to supplement the operating staff at important supply points by automatic equipment designed to perform such essential switching operations as quickly as possible, in order to minimize the duration of supply interruptions.

Mr. D. R. Barr-Wells (*at Newcastle upon Tyne*): The worth of any particular indication depends largely on its giving the control engineers adequate time to act. Means of control and intercommunication should be designed to save their time, particularly in periods of emergency or rapid load changes. It is debatable whether every one of the facilities provided fully measures up to this. However, much of a control engineer's work involves keeping logs. Automatic logging equipment will be provided at National Control (Section 5.6 of Paper No. 2626), and I feel that automatic logging, operated from the routine instructors, generator instructors and circuit-breaker indications, would have been an advantage at the G.C.C. and increase the worth of the routine instructors.

It is interesting that complete unanimity has been reached in the choice of a 'normally dark' diagram for all G.C.C.'s. Indeed, where many indications are displayed, this has been proved to be the only satisfactory form of diagram. It is unfortunate that most Grid Control Rooms require some artificial light all through the day. This would appear to have been dictated by security.

Combining telephone signalling with indications, etc., on the same channel could cause delay in putting through calls at busy periods.

In time it will be interesting to have further information on the performance (both operational and maintenance aspects) of the standardized system. This is well suited to C.E.G.B. system operation, and, as in many other fields, the experience gained will help all concerned with power-system control and communication abroad. However, it is evident that problems elsewhere are different, and other means of communications must be used. Sometimes, even different facilities must be provided for system control.

Dr. D. N. Truscott (*at Birmingham*): There are different ways of drawing the attention of engineers to matters which call for attention. The switching engineer is summoned by buzzer or lamp, giving an exact indication (*a*) that he is wanted, and (*b*) who or what needs his attention.

The loading engineer, on the other hand, is expected to discern a significant change which may occur at random in the indication of any one of the array of instruments in front of him. He is expected to do this without help of any kind. There is not even a second pointer on each instrument, corresponding to the hand-set pointer on the domestic barometer, to act as a short-term memory. The present arrangement clearly works satisfactorily for a large part of the time, but, under limiting conditions of fatigue, there is surely a grave risk of failure because the stimulus for the operator is weak and so he does not perceive a critical indication.

I am surprised that the loading engineer periodically calculates and signals to the C.E.G.B. National Centre the incremental and decremental costs. Is this not an instance for the use of a simple computer, preset for the major conditions at the station, which calculates these costs from time to time and transmits them to the Centre?

There seems to be a great deal of desk space in front of each engineer for papers to the exclusion of significant controls. If the engineers are recording information, could this not be done automatically?

Mr. E. V. Hardaker (*at Birmingham*): The outstanding feature of the papers is the high degree of standardization which has been adopted. Practically the whole of the equipment is of the telecommunication and electronic type, and manufacturers of such equipment are constantly developing new ideas. Experience in Birmingham with the old Grid Control Centre showed that, throughout the 25 years of its life, new ideas were tried out when extensions were required. Therefore, in view of the high degree of standardization, what provision has been made for accommodating new developments for which it may be considered desirable to obtain operating experience?

Towards the end of its life the Control Room premises in the Birmingham Centre had become very congested. On what basis is the ultimate capacity of each Centre planned? There must be a limit to the expansion which the switching and loading diagrams and the various equipment racks can accommodate?

Although the old equipment was in service for 25 years, the maintenance required had been excessive for the last 10 years, and the economic operating life of the equipment is estimated to have been 15 years. What is the estimated operating life of this equipment before maintenance becomes too excessive?

An endeavour has been made to achieve maximum economy as well as reliability on Post Office line rentals, by the adoption of what is referred to as a group system. This reduces to a minimum the number of lines from the Grid Control Centre to the outlying stations. Furthermore, in order to make maximum use of these lines, they can be used not only for system operation, but also for administrative purposes. These lines are perhaps too few in number for both purposes. Is this the experience of other Grid Control Centres? Quite rightly, system operation has priority on any line, but the administrative requirements must have a reasonable service, and I wonder whether some relief may be obtained by the introduction of a teleprinter service with the parent or major stations?

Reference is made in the papers to the use of Grid Control lines for intertripping purposes. Intertripping is essentially protection equipment, and its purpose is to isolate a fault as quickly as possible so that the damage at the point of fault is reduced to a minimum with the least possible disturbance to the remainder of the system. I therefore consider that this equipment should be as simple as possible, that an intertripping

operation between two points should be carried out over as direct a line as possible between these two points, and that it should be used for no other purpose. If Grid Control lines are used, there are two lines in tandem, with increased vulnerability, and there is a greater risk of interference due to the same lines being used for other purposes.

Limited selective control has been adopted in the Birmingham district, where five stations can be controlled from a central Control Room on the Hams Hall site. So far, experience with this equipment has been most favourable. We do not use Post Office lines, but have our own private pilots, and it is therefore unnecessary to provide any standby feature in the form of delayed automatic reclosing equipment. We were able to obtain pilots for this purpose because of the very wise policy adopted in the past of laying a pilot cable whenever the ground was opened up for laying main cables.

Mr. I. G. Edwards (*at Birmingham*): Certain precautions have been taken from the Civil Defence aspect, but I do not think that the control rooms have been moved far enough from target areas. The target area of a 20-megaton bomb is 20 miles. Has consideration been given to moving the Control Centres underground? They all appear to be on the surface, and therefore subject to blast and radiation.

Does the control engineer use v.h.f. equipment, and what type of gear is used at the receiving end by the engineer in the field? Is the equipment readily transportable?

Why was a.f. control not adopted before? It has been adopted in America with very satisfactory results, and it seems that the fact that the cross-Channel link was not developed on a.c. lines has retarded development in this country.

Mr. A. Abbott (*at Birmingham*): Control of a network like the British Grid system should be approached from the negative aspect, otherwise there can be a tendency for control merely for its own sake. Provided that each power station is assigned a specific loading, busbar voltage and reactive-power loading (import or export), generation engineers should be allowed to run their own machines and boilers. System control engineers should be concerned principally with the system, and concern themselves as little as possible with the power stations.

In Fig. 7 of Paper No. 2626, it appears that power-station control staff are being held responsible for local Area Board control. No doubt the idea is of economic advantage to the Area Board, but it could be, in evading the responsibility of controlling their own system, that the capital cost of the equipment involved plus the man-hour charges for operation are merely transferred from the one statutory body to another. Furthermore, under system emergency conditions, i.e. faults and instability, despite premeditated instructions, power-station control staff always pay first attention to prime movers and steaming conditions, leaving the system to fend for itself.

Mr. A. J. Davidson (*at Edinburgh*): The reasons given in favour of using Post Office rented circuits for the channels of communication are appreciated, but the reasons do not necessarily apply in all regions of the British Post Office.

I refer to the provision of zero-loss circuits, the cheapness of Post Office circuits in comparison with cables and power-line carrier and the immunity of Post Office circuits from power-system disturbances.

In our experience zero-loss circuits cannot be provided in all cases. In Scotland, Post Office circuits are certainly not cheaper. We have found that the power-line carrier outage record is remarkably good, and certainly much better than anything we could have obtained using Post Office circuits. For example, in the period March–October, 1958, the percentage of faults attributed to power-line carrier failure in the Board's system was 3·3%, which compares very favourably with the percentage failure of Post Office private circuits for a similar period in the north-east region of England, which was given recently at 16%.

The problem in the north of Scotland is very different from that in England so far as Post Office circuits are concerned. We seldom have the opportunity of benefiting from the normal expansion of the public telephone system, and, in nearly all cases, in circuits of any importance, we are required to meet a considerable capital expenditure in addition to the standard charge. This capital expenditure can often make the Post Office circuit more expensive than the power-line carrier.

The statement on aerial pilot cables is slightly misleading as I can confirm that an operational embedded earth-wire pilot cable does exist on Grid towers in our Area, namely between Brechin and Bridge of Dun on the Aberdeen–Dundee 132 kV line over a distance of 3·2 miles. This is an isolated case, but the information is given since the installation has not so far given any trouble in service.

The stated basic technical disadvantages of using power-line carrier are also somewhat misleading.

I cannot agree that icing conditions are of any importance to power-line carrier transmission in Great Britain. In spite of the fact that, theoretically, conductor icing can increase the attenuation above normal by as much as four or five times, it is our experience that the increase in signal attenuation due to icing of the power conductors on any particular circuit is so small as to be considered negligible. Indeed, we have attempted to use the increase in attenuation to detect the presence of ice, but, so far, we have been unable to record any appreciable change in the normal circuit loss. This is certainly due to the fact that the iced section of a particular line comprises a very small percentage of the whole, and, in our experience, this result has been general. The Board operate the highest-altitude lines in Great Britain. Those from Fort Augustus to Aberdeen and Errochty traverse the Corrieyairack Pass at 2 507 ft, and the Aberdeen line traverses the Lecht, one of our notorious storm points near the Devil's Elbow, which is usually the first and last point in the north to be severely affected by snow and ice.

In our experience power-line maintenance causes little, if any, interruption to power-line carrier transmission. It has been found that maintenance, requiring application of local earths, etc., to power conductors on towers not in the immediate vicinity of the terminal substation, makes little difference to the line attenuation, and the slight change caused can be readily compensated in the power-line-carrier receiving equipment. In some instances, compensation is unnecessary, since, from an operating point of view, no loss of facility is reported or indeed has occurred.

Local earths applied to the conductors within three towers of the line-coupling equipment do have an effect, but the work in this restricted length of line is usually of short duration and the inconvenience is acceptable. There are, as a rule, alternative routes of communication which can be used. However, the effect on signal attenuation of portable earths applied to Grid conductors is not always constant, and it has been noted that the effect on attenuation of carrier telephone circuits using double-circuit power lines is considerably less than on circuits using single-circuit lines. Since a proportion of the h.f. signal is being carried by the parallel 132 kV circuit, this effect is understandable.

Whereas the same frequency cannot be used on lines which are inductively coupled, it is also true that, by careful planning, even in a complex network like that of the Board, the same frequency can, and indeed is, used more than once. The separation required to ensure that any one circuit does not interfere with another was taken some years ago at three-section spacing, and I can confirm that it has been effective. This separation does impose a restriction, but it is a planning problem which has not

so far proved insurmountable. We have not yet exhausted the frequency repetition possible; the upper limit at present is 480 kc/s. I see no reason why power-line carrier transmission could not be applied in the 500 and 600 kc/s bands, at least on lines under 50 miles long operating on phase/phase basis. This will reduce the need for repetition of frequencies even more.

The stated objections to power-line carrier transmission cannot be said to apply to the whole Grid network, and I feel that a balance between power-line carrier and Post Office rented circuits might have proved more acceptable than almost 100% reliance on Post Office circuits.

Mr. J. H. Henderson (*at Edinburgh*): The standards applied for the transmission of speech are from 300 or possibly 400 c/s to 2 kc/s, the upper frequencies being used where necessary for the provision of various indication, metering and control facilities. The accepted loss on a circuit can be up to 20 dB between the Grid Control Centre and a major station and 25 dB between the Grid Control Centre and a minor station. The loss at 2·4 kc/s might be 10 dB worse than the 800 c/s figure.

It seems remarkable that, in building up a communication network, so little should be demanded of the basic unit in the network, i.e. the telephone lines themselves. It may be difficult or costly to obtain higher-grade circuits from the Post Office, but, in order to have as high an intelligibility as possible for passing vital messages concerning switching operations, etc., a few hundred cycles per second more would have effected an appreciable improvement.

What is the cross-over frequency of the speech-separating filters, and how much of the bandwidth is lost owing to the quality of the filter?

What were the reasons for choosing the discrepancy type of diagram instead of a continually illuminated one? Has the use of message instructors been proved effective in practice, and why were they used in preference to telephone instructions?

What prospect is there of operating the present equipment with transistors, and would the station 50-volt battery be used for this purpose? Is it intended to replace the cold-cathode-tube multiplexing by transistor switching?

Mr. W. J. A. Painter (*at Leeds*): In his introductory remarks when presenting the papers, Mr. Gunning suggested that the size of the supply system in this country necessitated a new standardized flexible system. I suggest that it was the change in character of the system, resulting in increased demands for information by the control engineers, which necessitated the new system, and that it was the rate of growth of the primary system which caused a flexible indicating system to be required. Nine months' experience in this Area has already fully justified the flexibility of the system described and its ability to permit control-room displays to keep pace with primary system changes, which was not possible with the system in use for the past 25 years. On the other hand, the previous system in use in this Area had a very low fault rate, and we were apprehensive about the new system and the maintenance which might be required. Our fears have been allayed by the particularly good performance to date.

Section 3 of Paper No. 2626 deals with channels of communication. Pilot cables are rightly dismissed on economic grounds. The author has given some reasons for the choice of rented Post Office pilots, and I would add two further reasons against the use of carrier on a tightly knit system like that of the British Grid. A carrier system requires a suitable focal point on the network, and the Grid system is frequently changing its character and focal points as each new power station or major substation is commissioned. Moreover, such changes in line disposition and the constant introduction on the system of new Grid supply points would mean a constant shift of equipment from station to station, and this at a time when all communication and indication facilities are needed whilst construction work and commissioning is in progress. Could the author reinforce his statement on the satisfactory performance of Post Office lines by quoting the line-fault record over the 25-year period mentioned?

Having decided on the use of Post Office lines, I regret that the design of the equipment was kept within the 2·4 kc/s band when the Post Office was rapidly improving their lines. It would have been better to have standardized at a higher frequency with temporary restrictions to 2·4 kc/s on some lines rather than have a permanent limit of 2·4 kc/s on all lines and wastage of the band above on many lines.

Experience to date suggests that greater use should be made of four-wire circuits, especially between the major stations.

Can the authors define the accuracy of 1% of full scale claimed for the telemeters in Section 6.4 of Paper No. 2627. The response time is defined as that taken to indicate 80% of a change of reading. What is the time taken to come within the 1% accuracy claimed? Do system conditions change so fast that this accuracy is seldom reached and may therefore be unjustified?

In Section 8 of Paper No. 2626 the author refers to future developments. I suggest that accelerated tripping facilities can be employed only where the communication network conforms to the pattern of the primary system. This might have been the case had a carrier system been employed, but it does not apply where Post Office lines are used. I believe that this facility will have limited application. I also suggest that the application of automatic frequency control is not economically justifiable in this country.

One future development is a larger limited selective control system. The system described is based on a single-switch 132 kV Grid supply point as shown in Figs. 7 and 8. Present-day supply points frequently consist of 3- or 4-switch 132 kV mesh stations with three transformers, and the existing L.S.C. system is not able to provide all the facilities required. Can the T.T.C. develop a system with more facilities?

Will the T.T.C. also develop a transistorized version of many parts of the equipment for incorporation in future, and indeed existing, equipments, thereby avoiding the oft-repeated objection that standardization means sterilization?

Mr. E. W. Connon (*at Manchester*): There are, of course, many points of detail in the equipment which can be criticized, but perhaps the greatest criticism might be the time which the project has taken. According to the papers, the B.E.A. decided on the programme in 1949 because the existing equipment was then 15 years old. But it is now 10 years since this decision was taken, and while this delay was almost inevitable, we should not overlook its results in an age of rapid progress.

The new equipment, whilst giving the control engineer a much improved service, nevertheless gives him the same kind of information as the old. It is unfortunate that control procedures were not more critically reviewed so that the equipment could have been arranged not only to present the information but perhaps to process it into a more digestible whole.

Similarly, the control engineer continues to give his switching instructions by telephone, and the obvious mistakes and misunderstandings sometimes occur. I do not suppose that there is any technical difficulty in arranging for the control engineer to initiate directly his own switching and, perhaps, in providing him with an automatic preview of its results before he makes it effective.

The limited selective control equipment mentioned in Section 6.3 does, of course, give us a means of dealing with the problem which arises when an old power station is closed down or put on two-shift manning by enabling us to transfer the control

to some other manned point, but this may, in its turn, be demoted to two-shift manning. Might it not have been better to have gone the whole way and given direct control from the Control Room?

The engineers in the Grid Control Room have an onerous duty to run the system at the lowest cost commensurate with reasonable security. Perhaps they should be aided in their job by some form of process-controlling computer which would analyse the situation from minute to minute and give them the guidance which is now becoming the practice in other process industries. They would thus be able to take account of transmission losses, which are, at present, largely left out of the picture because of the complicated and laborious calculations involved.

Process-controlling computers are now being actively considered for ensuring the most efficient operation of power stations, and one visualizes that some feedback from these station computers to the Control Room would enable the control engineer to operate on more accurate and up-to-date cost information.

Mr. C. Ayers (*at Manchester*): Having seen one of the new Grid Control Centres containing a control board some 75 ft long, housing approximately 1 500 semaphores and 100 telemeters, I have formed the impression that the limit of the control engineer to assimilate information has been reached. Is this in fact the case, and has too much detail been attempted in too few Control Centres?

In the past, power generation has generally taken place in the coalfields, and control was a local problem apart from weak tie-line control. Now that nuclear power is with us, resulting in the bulk transfer of power through Areas, is the present system of control sufficiently flexible to cover this problem and also that resulting from the loss of 200 or even 550 MW of power at any one time?

The equipment for the Grid Control Centres is located in open-type telephone racks, and no type of air-conditioning system has been provided. Have any deleterious effects from dust and concrete during construction stages been observed?

With regard to the layout, are the heat sources, such as valve heaters, etc., located so as to avoid chimney effects resulting in air and dust movement over contacts?

I understand that the telemeters giving the load-flow indications in the G.C.C. return to zero on the occurrence of a fault. Would it not be advisable to warn the operator of a fault and leave the telemeter locked at its last 'healthy' reading?

For generating-station load, instruction telemeters are provided for operation in 1% steps. What is the degree of accuracy desirable in the following of such instructions by the respective stations?

Mr. R. C. Eastwood (*at Manchester*): The equipment in the Manchester Grid Control Area has been in use for nearly a year. It comprises some 390 circuit-breaker indications and 180 meters, and can select 150 control telephones. It is one of the largest installations in the country and will be increased by approximately one-third of its present size during the coming year. The design work has been carried out so successfully that this rapid development presents little difficulty and will, in fact, be largely a routine matter.

During a week we handle about 20 faults, three of which are on the Post Office private wires. Faults generally divide themselves into one half on the electronic telemetering system and the rest between telephony and indication. As a rule they become evident by the total loss of a particular service, but some, usually speech deterioration in telephony or scale errors in metering, can be found and kept in check only by a routine system of maintenance. It is thus hoped gradually to decrease the fault level until only private-wire and component-failure faults remain.

One small complaint about the system is that too little has been done for the administrative telephone traffic. I know that it is often more economic to use the Post Office telephone than to provide a private-wire service, but this is a poor by-product of an operational telephone system.

Mr. E. Sykes (*at Manchester*): The new equipment and the new Control Room are very much better than the old, but I have a few minor criticisms.

There are too many alarms in the Control Room. Bells are ringing all day long, and most of the time they do not signify anything very important. For example, if a line trips on a fault, the switches open at each end, and the audible and visual alarms come up in the Grid Control Room. That is the proper function of an alarm. However, if the line is taken out for maintenance, the switches open at each end, and the alarm sounds in the Control Room just the same. But, in this case, there is no need for an audible alarm to bring the control engineer's attention to what is happening, since he gave the instructions for these switches to be opened. It is still desirable, however, to have the visual-discrepancy lamps at all times.

Switches are opened for maintenance much more frequently than for faults, and a subconscious defence mechanism comes into action which makes the control engineer partially deaf to all these maintenance alarms. This is a disadvantage when, once in a thousand times, the alarm means that a line has tripped on fault. Could it be arranged that a switch opening on fault would sound an alarm, and a switch opening for maintenance would not? Could this be done by operating the audible alarm from the tripping relay instead of the switch whilst still operating the discrepancy lamp from the switch?

Mr. J. Simpson (*at Manchester*): In order to further the continuous efforts which the Area Boards are making to improve their load factor, would it not be possible to extend the present indicating equipment so as to provide a continuous indication of the Area Board load both in the Grid Control Room and at, say, Area Board Headquarters? An immediately available indication of the system load could enable the Boards to formulate and implement tariffs, providing an incentive to those consumers who, on demand, would reduce their load at potential peak-load periods. This, in turn, would improve the Board's load factor and could reduce the amount of generating plant to be installed by the C.E.G.B.

Messrs. P. F. Gunning, G. A. Burns, F. Fletcher, and C. H. Chambers (*in reply*): The operation of large power networks depends to a great extent upon the efficiency of the associated telecommunication systems, but even the best telephone system cannot be efficient if the users have to contend with background noise. Usually the remedies are quite inexpensive. The early Grid Control Centres (G.C.C.'s) suffered badly from room echo but were quite satisfactory once pile carpets had been laid. The new G.C.C.'s have sound-absorbing material on walls or ceilings and/or carpet.

It is usual to avoid mounting relays with thermionic equipment, but with the multiplex telemetering equipment the only benefit of miniaturized electronic equipment would have been lost since, with separation, much more mounting space would have been required, and there would have been serious fault liability with the considerable increase in jack-in connections. Troubles referred to by Mr. Sealy ceased once back-plates had been removed to ventilate groups and relays near a hot spot had been replaced by an electronic equivalent. There should be no troubles from heat with the transistorized versions now being developed. In the electronic 'system frequency' slide-wire indicators the vibrating synchronous switch contacts became

contaminated by vapours driven off from the insulation material. This was cured by using a more inert insulation material and by placing an activated carbon getter inside the can.

Over recent years intertripping equipment has become expensive with the premise that it should have its own signalling channel(s) and cubicles. This is inconsistent with the accepted practice of limited selective control equipment which is freely connected to station tripping and closing leads and yet is part of the general indicating and telephone network. Mr. Hardaker does not favour intertripping over signalling circuits in tandem, and yet there is no practical alternative for multi-ended feeders. A return to the well tried and much less expensive arrangement of intertripping with equipment inside the Grid control cubicles using the Grid control networks is overdue. Such an arrangement would be fast enough for normal purposes and would suit multi-ended feeders. High-speed intertripping over power-line carrier for transformer protection is a problem since regulations restricting radiation from power lines preclude the continuous transmission of guard signals of sufficient strength to withstand hoar-frost attenuation on long lines and because the general operation of power-line isolators can shock 'operate' carrier receivers in the vicinity.

Modifications to the standardized system are tried out by the Divisions from time to time, and when approved by the T.T.C. are applied to all stations by the manufacturers. In this way the ideas of individuals benefit the country as a whole. Mr. Birch has presented a satisfactory record for the Newcastle control area, which was one of the earlier installations. When modifications from the later installations have been applied the record should be even better.

Consistent with Post Office practice, the ringing tone is returned to the caller when the call matures and the 'busy' tone to other than control engineers when the called party is engaged. In the absence of these tones the calling party is immediately aware that equipment or lines are out of order.

With the speedy restoration of bulk supplies and transmission capacity at unattended stations by means of automatic reclosing equipment, the next stage, as Mr. Birch suggests, will be to provide it at attended stations, which is common practice in the United States. The general application of high-speed auto-reclosure to the 275 kV system is already under way, and delayed auto-reclosure is to be provided at an increasing number of 132 kV generating stations.

There was little scope for standardization while manufacturers made equipment to suit individual tastes. Real progress was made only when, in 1948, the operation engineers of the British Grid system, after many years of experience, collectively standardized their requirements, even though, as Mr. Barr-Wells suggests, the value of specific standardized facilities may be debatable. With the increasing use of automatic aids, provided that the record is worth the cost of automatic logging equipment, arduous logging may become a thing of the past. The Manchester Grid control engineers' conversations are recorded, but they are played back only after abnormal occurrences; otherwise the record is erased after 24 hours.

The G.C.C.'s are designed for round-the-clock operation, and therefore artificial light is of paramount importance. However, despite this and the emphasis on security, the system operation engineers have managed to create a daylight atmosphere in the new G.C.C.'s.

There is no noticeable delay in putting through telephone calls on lines used for indication signalling. A telephone call is transmitted in one second, and an indication train in seven seconds. Telephone calls are interlaced between successive indication trains. Conversations are unaffected by telemetering or indication traffic.

With regard to Dr. Truscott's plea on behalf of the loading engineers, we cannot think of any significant change not brought to their attention, since the individual station generation telemeters have target pointers, as also have the system frequency, area net transfer and area generation indicator-recorders. In addition, the individual Grid lines have automatic current-overload and line-end-open indications.

The revision of incremental and decremental costs usually requires no more than a glance at the schedule of individual machine generation costs. Under present methods of operation, a computer with automatic transmission is not warranted. The spare operating space on the loading desk (4 ft^2) was specified as an insurance against such possibilities as dispatching computers, v.h.f. radio and automatic frequency control.

The development of the standardized system is a continuing process, additions being accommodated without restriction by the use of standardized basic units, and although loading and switching diagrams may change and even be replaced to suit changing requirements, the new Control Rooms each with 2 500 ft^2 of floor space should still be in service in 20 years time. Apart from the electronic telemetering equipment which is designed to carry continuous traffic indefinitely, the standardized system is lightly loaded, and provided that it is not out-moded, it should require no more maintenance in 20 years time than it does at present.

The Grid control networks are planned on the group system to provide maximum security; any economy in line rental is incidental. The group system greatly benefits district staffs and the headquarters of Divisions without G.C.C.'s. Unless the C.E.G.B. agrees to expand the control networks considerably to carry 40-hour-week administration traffic in its entirety, Divisional Headquarters, which previously accommodated the old G.C.C.'s, may now perhaps have a restricted service and have to make more use of the public system.

Laying pilot cables in the same trench as power cables fed from resistance earthed systems is an established practice, but with solidly-earthed single-phase 132 kV cables, depending upon length and local shielding factors, precautions may be necessary to prevent breakdown of pilot cables and terminal equipment on the occurrence of Grid faults.

We agree with Mr. Edwards that some of the security precautions adopted by the B.E.A. in the early 1950's for Grid control may now be out of date, but, despite the magnitude of the problem, recent measures based on dispersal with common-channel v.h.f. radio as standby are realistic and practical.

The C.E.G.B. uses mobile v.h.f. radio extensively, with one common single-frequency channel for power-line maintenance and construction and another for service around nuclear power stations; the colliers use a common two-frequency channel. Telephone operators at power stations in the South-Eastern Division connect mobile stations to the control network.

Automatic frequency control is required in loosely-knit power pools in which each participant is obliged to run spare plant, irrespective of power-pool merit-order generation, to cover his own load variations and largest machine failure. In Great Britain, with a tightly knit 24 GW power pool under merit-order generation and unified control and with no a.c. connection to neighbouring countries, automatic frequency control could be justified only if there was inadequate transmission capacity between control areas. If and when the need arises the system which was developed by the B.E.A. and tried out some years ago* should meet the C.E.G.B. requirements.

Mr. Abbott is mistaken in assuming that power-station staffs who operate Area Board switches are held responsible for system

* MORAN, F.: 'Power System Automatic Frequency Control Techniques', *Proceedings I.E.E.*, Paper No. 2871 M, November, 1958 (106A, p. 145).

control by Area Boards evading their responsibilities. It would be grossly uneconomic if Area Boards had to control their switches in stations controlled by the C.E.G.B., and it would certainly not be in the public interest if such control went by default, or in keeping with the co-operation which exists between the C.E.G.B. and the Area Boards, who control quite a number of Grid stations for the C.E.G.B.

The C.E.G.B. uses power-line carrier extensively for the protection of long feeders, rented circuits being used for short feeders. In January, 1959, during two days of hoar frost, carrier protection was affected on five power lines in the East Midlands plain. If similar installations in the Highlands are unaffected, it may well be that the power lines are not so long or, being shielded by the terrain, are only partially exposed to hoar-frost conditions.

Between the majority of stations and the G.C.C.'s, speech level is very much better than the economic planning limits of 20–25 dB, which obtain in a few instances at unattended stations. As stated in the London discussion, the band above 2 kc/s is deliberately reserved as an insurance against future requirements. It should be noted* that, to increase the capacity of the trans-atlantic cable between London and Montreal, 2 kc/s spaced channel equipment has been in operation since December, 1957, as a temporary measure without attracting adverse criticism.

Illuminated discrepancy indications in large switching diagrams, especially in well-lit Control Rooms, are operationally much superior to continuously illuminated indications, since they are easier to perceive and maintain. Well proven over the last 20 years as a valuable adjunct to the telephone system, message instructors are provided in the standardized system to broadcast stereotyped instructions to outstations. Thus, in an emergency, engineers are able to deal with the situation without making a series of telephone conversations.

We are unable to give Mr. Painter performance figures for Post Office lines over the last 20 years, but the results of a survey in 1954–55 showed that lines, on the average irrespective of length, were out of order for 22·22 hours in a year. Coincidence of Post Office line failure with system fault is extremely rare.

Accurate (1% full-scale deflection) telemetering is essential if instructions concerning generation and area net transfer are to be carried out without argument, or automatic control is to be satisfactory. Telemetering with a response of up to 2 min delay is quite adequate for manual load dispatching. Fast-response telemetering is required only for automatic net transfer control. In the standardized system, feeder flow telemeters respond within 15 sec to indicate 80% of any change and they show the full change within 45 sec. While this performance may be more than adequate, what is important is that it is derived from quite ordinary induction meters slowly impulsing up to one impulse a second for full scale and that ten of these telemeters require only the same 120 c/s bandwidth signalling channel as one fast telemeter.

Using the Grid control networks accelerated tripping is being provided at an increasing rate. Since the signalling requirements are simple, G.C.C.'s could be developed to relay signals between stations in the area.

The T.T.C. has recently developed the Mark II Minor System. This displaces the original Minor System and caters for limited selective control. The term 'limited' is now a misnomer since the Mark II System will operate over any channel and distance and has the capacity for 400 single-point indications and 100 single-point controls. The new system creates parent and satellite minor stations and is also to be used to control over tie lines the Grid switches at single-shift major stations.

Because the B.E.A. embarked on standardization in 1948 is no reason to suppose the standardized system to be ten years behind the times. Being extensible and flexible, features are continually being discarded and new facilities added, thus keeping in step with the latest technical developments and operational requirements. The presentation of information in the G.C.C.'s was very carefully planned to facilitate easy comprehension of the overall situation. The layout of the desks and diagrams was based on current ergonomic theory. A considerable amount of information is, in fact, processed. Quantities such as inter-area line flows and station outputs which must be individually displayed are summated; the rate of change of frequency is displayed. As Mr. Connon suggests, further processing of information will require the introduction of computers. The need for these is appreciated and their detailed requirements are already being considered. There is no difficulty in remotely controlling Grid switchgear from G.C.C.'s. The C.E.B. used to do it from the Bristol G.C.C. under system split conditions to relieve small generating stations of the burden of charging long Grid lines. With security of the Grid as the first consideration and having regard to the complexity of the control networks, it has always been a basic axiom of Grid control, as distinct from distribution control, to operate switches from the nearest attended point and not from G.C.C.'s, where the control engineers are fully occupied with the system as a whole.

We agree with Mr. Ayers that, in due course, one or two more G.C.C.'s may be required, but, with the shutting down of old power stations and the introduction of large 600–2000 MW stations, the total number of power stations is not increasing. If switching diagrams become congested with the continual addition of Grid stations, we may have to adopt disjointed diagrams as in the Leeds G.C.C.

The absence of air-conditioning plants at the G.C.C.'s has not had any deleterious effect on the open-type equipment racks; construction did not begin until the buildings had been dried out and the composition or block floors laid. Telemeters return to zero on the occurrence of a fault and a lamp lights in the face of the instruments, thus warning the control engineer. Leaving meters locked to the last reading is reminiscent of 'on demand' telemetering and can be misleading.

We sympathize with Mr. Sykes, but his trouble results from a local decision to 'strap' the universal alarm equipment to repeat unacknowledged alarms at regular intervals, and from maintenance staff at outstations not making full use of circuit-breaker test links. To provide an audible alarm only when circuit-breakers are tripped on fault would not be difficult, but it would be expensive to marshall trip-signal initiation at some 400 stations.

With reference to Mr. Simpson's request for continuous indication of Area Board load at Area Board Headquarters from the associated G.C.C. or G.C.C.'s, there is no technical problem; it is purely a matter of expense, bearing in mind that the boundaries of the 11 Area Boards in England and Wales are quite different from the boundaries of the seven Grid Control areas.

* *Post Office Electrical Engineers' Journal*, 1959, 52, Part II, p. 141.

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Part A. POWER ENGINEERING, FEBRUARY 1960

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